Program
Lunar ISRU 2019: Developing a New Space Economy Through Lunar Resources and Their Utilization

July 15–17, 2019 • Columbia, Maryland

Institutional Support

Lunar and Planetary Institute
Universities Space Research Association
NASA Lunar Exploration Analysis Group

Co-Conveners

Stephen Mackwell
American Institute of Physics
Clive Neal
University of Notre Dame
Christopher Pestak
Universities Space Research Association

Science Organizing Committee

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Colorado School of Mines
Dale Boucher
Deltion Innovations Ltd., Canada
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NASA Human Exploration and Operations Mission Directorate
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NASA Johnson Space Center
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NASA Office of the Administrator
Gerald Sanders
NASA Johnson Space Center
Nantel Suzuki
NASA Human Exploration and Operations Mission Directorate
Guide to Sessions

Lunar ISRU 2019: Developing a New Space Economy Through Lunar Resources and Their Utilization
July 15–17, 2019
Columbia, Maryland

Monday, July 15, 2019

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<tr>
<th>Time</th>
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<tr>
<td>8:30 a.m.</td>
<td>USRA Conference Center</td>
<td>Introduction and Updates</td>
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<tr>
<td>1:15 p.m.</td>
<td>USRA Conference Center</td>
<td>Marketing of Resources</td>
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<tr>
<td>5:00 p.m.</td>
<td>USRA Education Gallery</td>
<td>Poster Session: Characterization</td>
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<tr>
<td>5:00 p.m.</td>
<td>USRA Education Gallery</td>
<td>Poster Session: Identification of Resources</td>
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<td>5:00 p.m.</td>
<td>USRA Education Gallery</td>
<td>Poster Session: Marketing of Resources</td>
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Tuesday, July 16, 2019

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<tr>
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<td>USRA Conference Center</td>
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<tr>
<td>5:00 p.m.</td>
<td>USRA Education Gallery</td>
<td>Poster Session: Extraction of Resources</td>
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<tr>
<td>5:00 p.m.</td>
<td>USRA Education Gallery</td>
<td>Poster Session: Processing of Resources</td>
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Wednesday, July 17, 2019

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<td>Extraction of Resources</td>
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<td>USRA Conference Center</td>
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<td>Times</td>
<td>Authors (*Denotes Presenter)</td>
<td>Abstract Title and Summary</td>
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<tr>
<td>8:30 a.m.</td>
<td>Neal C. *</td>
<td><em>Introduction and Workshop Logistics</em></td>
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<tr>
<td>8:40 a.m.</td>
<td>TBD *</td>
<td><em>NASA — Going Forward to the Moon</em></td>
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<tr>
<td>9:00 a.m.</td>
<td>Picard M. *</td>
<td><em>Canadian Space Agency</em></td>
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<tr>
<td>9:20 a.m.</td>
<td>Makaya A. *</td>
<td><em>European Space Agency</em></td>
</tr>
<tr>
<td>9:40 a.m.</td>
<td>Martin G. *  Lamboray B.</td>
<td><em>The Luxembourg Perspective on ISRU and the Development of a Commercial Space Ecosystem</em></td>
</tr>
<tr>
<td>9:55 a.m.</td>
<td>Suzuki N. *</td>
<td><em>NASA — ISRU Perspective</em></td>
</tr>
<tr>
<td>10:15 a.m.</td>
<td>Acierno K. *</td>
<td><em>iSpace and Lunar Resources</em></td>
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<tr>
<td>10:30 a.m.</td>
<td>Break</td>
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<tr>
<td>10:45 a.m.</td>
<td><strong>Moderator:</strong> Sowers G.  <strong>Panelists:</strong> Barnhard G. Kelsey L. Blair B.</td>
<td>Panel: <em>Commercial Lunar Propellant Architecture Study</em></td>
</tr>
<tr>
<td>12:00 p.m.</td>
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<td><strong>Lunch</strong></td>
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<tr>
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<tr>
<td>1:15 p.m.</td>
<td>MacDonald A. *</td>
<td>What are ‘Markets’ for Lunar Resources?</td>
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<tr>
<td>1:25 p.m.</td>
<td>Christensen C. *</td>
<td>Lunar ISRU Markets Within Broader Economic Context</td>
</tr>
<tr>
<td>1:40 p.m.</td>
<td>Marquez P. *</td>
<td>Space Resource Markets and Lessons Learned</td>
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<tr>
<td>1:55 p.m.</td>
<td>Jones C. *</td>
<td>Exploration Architectures and Lunar ISRU</td>
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<td>Our research proposes an integrated ISRU evaluation framework through the network-based space logistics architecture and analyzes the performance of ISRU by considering plant deployment, regular production operations, and propellant storage.</td>
</tr>
<tr>
<td>2:15 p.m.</td>
<td>Gelino N. J. * Buckles B. C. Mueller R. P.</td>
<td>Construction of infrastructure is the Key to Establishing a Cislunar Economy (*5072)</td>
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<td>Government funded infrastructure in Cislunar space and on the lunar surface will be pivotal in establishing a Cislunar economy. Government, industry, and academia must define the highest return on investment areas for government funded infrastructure and develop it.</td>
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<tr>
<td>2:20 p.m.</td>
<td>Blair B. R. *</td>
<td>Emerging Markets for Lunar Resources (*5046)</td>
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<tr>
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<td>Recent movements in commercial space investment have inspired quantitative market models for lunar propellant and related commodities on the lunar surface, Earth-Moon Lagrange points, in lunar orbit, and in high-traffic inclinations of Earth orbit.</td>
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<tr>
<td>2:25 p.m.</td>
<td>Bienhoff D. G. *</td>
<td>Markets for Lunar ISRU Products and Their Value (*5018)</td>
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<td>Lunar ISRU products and their value as a function of use location for CSDC’s architecture is discussed. A high early value is critical to in situ resource development. Value as a function of launch cost is another hurdle that must be overcome.</td>
</tr>
<tr>
<td>3:00 p.m.</td>
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<td>Discussion: Markets for Lunar Resources</td>
</tr>
<tr>
<td>3:15 p.m.</td>
<td>Meurisse A. * Carpenter J.</td>
<td>ISRU: An Approach to Change and Knowledge Gaps to Fill for Viable Processes in Space (*5005)</td>
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<td>As an interest in ISRU is emerging again, it is important to understand the failure of the past. This work offers a critical look at the past considerations of ISRU activities and proposes a new focus for developing the field in the long-term.</td>
</tr>
<tr>
<td>3:20 p.m.</td>
<td>Bennett N. J. *</td>
<td>An Existing Market for Lunar Propellant — GTO Orbit Raising as a Service (*5043)</td>
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<td>GTO orbit raising is an existing market for lunar sourced propellant. This market can charge higher prices per kilogram and be serviced by a much smaller mining operation than a LEO market; these factors translate to significantly higher returns.</td>
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<td>Panelists:</td>
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<td>3:25 p.m.</td>
<td>MacDonald A.</td>
<td>Christensen C. Marquez P. Jones C.</td>
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| Colaprete A. Elphic R. C. Shirley M. | **Characterizing Lunar Polar Volatiles at the Working Scale: Going from ISRU Goals to Mission Requirements** [#5025]  
This paper presents new geostatistical analysis and modeling to quantify critical parameter scales and mission requirements for adequate characterization of polar volatiles. |
| Vonstad F. K. Ferreira P. | **Using an Interdisciplinary Sample Testing Framework for Borehole Cores** [#5051]  
The research proposed is to create an interdisciplinary Sample Testing Framework for space utilization, combining Earth sciences with current astrobiology testing. This would be done using the newly developed Sample Testing Framework. |
| Barnhard G. P. | **Surface-to-Surface Power Beaming** [#5093]  
Space Power Beaming & Ancillary Services (SPB&AS) technology to be used to provide wireless utility services (e.g., power, data, communications, navigation, time, heat, etc.) in the lunar environment in a cost and resource effective manner. |
| Battler M. Faragalli M. Reid E. Cole M. Raimalwala K. Smal E. Vandermeulen M. Aziz M. | **Supporting ISRU Missions Through Mission Control Software** [#5095]  
Mission Control Space Services Inc. is developing mission control software to address emerging operations and autonomy needs in upcoming privately-led lunar ISRU missions, including improved guidance/navigation/control, communication, and data needs. |
| Wilkes J. M. | **Greenhouses as the Source of Rare Lunar Resources** [#5102]  
This paper is a discussion of what one would grow in a lunar greenhouse and why. Food and medicine will be mentioned, but the focus is on materials to construct, furnish, operate, and maintain a lunar base which are easiest to import as a seed. |
| Shukla S. Kumar S. Tolpekin V. A. | **Revisiting the Retention Framework of Lunar Helium-3 Through Space Weathering Processes and Its Implications** [#5108]  
A new space weathering perspective for precisely characterizing lunar Helium-3, wherein higher retentivity of hydrated pyroclasts is observed as part of preliminary survey. Such regoliths provide potential mining sites to develop lunar energy market. |
A new X-ray diffraction/X-ray fluorescence instrument will aid in resource exploration and process monitoring. |
| Joshi D. R. Eustes A. W. Rostami J. Dreyer C. Zody Z. Liu W. | **Using Real-Time Drilling Data to Characterize Water-Ice on the Moon** [#5127]  
This paper offers the details of the design of the test drill unit based on heritage drill systems used by NASA and others. The paper discusses the acquisition and analysis of the drilling data to assess the strength and water content in the PSRs. |
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<tr>
<td>Brown H. M.  Robinson M. S.  Boyd A. K.</td>
<td><strong>Identifying Resource-Rich Lunar Permanently Shadowed Regions</strong> [#5035]  We compare the lunar polar volatile datasets in order to identify sites that are most likely to host volatiles, and rank PSRs by resource potential.</td>
</tr>
<tr>
<td>Jozwiak L. M.  Patterson G. W.  Perkins R.</td>
<td><strong>Mini-RF Monostatic Radar Observations of Permanently Shadowed Crater Floors</strong> [#5079]  We used Mini-RF to analyze the CPR of flat PSR and non-PSR crater floors at the lunar north and south pole. No significant differences in the CPR were observed, suggesting water ice may not be preferentially concentrated in shadowed regions.</td>
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<td>Barker D. C.</td>
<td><strong>Lunar Resources: From Finding to Making Demand</strong> [#5083]  The current model of spaceflight is insufficient to kick-start off Earth ISRU, mining and usage of lunar resources. A paradigm shift, either by NASA or privately, must be initiated in a sustainable and long-term manner, if actual headway is to occur.</td>
</tr>
<tr>
<td>Schmitt H. H.</td>
<td><strong>Lunar Helium-3 as the Foundation of Lunar and Mars Settlement and an Earth-Moon Economy</strong> [#5084]  The fusion of lunar helium-3 with itself or with deuterium offers the promise of environmentally benign electrical power on Earth, and flexible and rapid interplanetary propulsion.</td>
</tr>
<tr>
<td>Lamboray B.  Link M.  Martin G.</td>
<td><strong>The Luxembourg Perspective on ISRU and the Development of a Commercial Space Ecosystem</strong> [#5105]  This presentation is an overview of activities undertaken by the Luxembourg Space Agency to support each of its five strategic pillars and provides the progress it has made, including results from the ISRU Value Chain Study and the Mining Space Summit.</td>
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<tr>
<td>Cook J. G.</td>
<td><strong>An Exploration Architecture for the Moon and Mars</strong> [#5106]  The aim of this presentation is to provide a thoughtful roadmap for a focused Mars and Moon exploration campaign integrating robotics, human, and commercial activities.</td>
</tr>
<tr>
<td>Faragalli M.  Reid E.  Battler M.  Raimalwala K.  Smal E.  Vandermeulen M.  Aziz M.</td>
<td><strong>Supporting ISRU Missions Through Mission Control Software</strong> [#5115]  Mission Control Software is an end-to-end operations software stack designed for rapid and on-demand deployment. MCS allows operators to easily and securely access mission data, and enables autonomy at multiple points in the operation.</td>
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<td>Cohen B. A.  Hayne P. O.  Greenhagen B. T.  Paige D. A.  Seybold C. A.  Baker J. D.</td>
<td><strong>Lunar Flashlight: Searching for Accessible Water Frost</strong> [#5120]  Lunar Flashlight is a NASA cubesat to be launched in 2020 to detect and map water ice in permanently shadowed regions of the lunar south pole and understand the resource potential in these areas.</td>
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<td>Ignatiev A., Curreri P., Sadoway D., Carol E.</td>
<td><strong>The Use of Lunar Resources for the Construction and Operation of a Lunar Radio Observatory on the Moon</strong> [#5011] &lt;br&gt;The resources of the Moon can be used to develop a radio astrophysical observatory on the far side of the Moon by fabricating a strip wire antenna or a dipole antenna array by thin film growth technology in the vacuum environment of the Moon.</td>
</tr>
<tr>
<td>Ignatiev A., Sadoway D., Curreri P., Carol E.</td>
<td><strong>The Use of Lunar Resources for Energy Generation on the Moon</strong> [#5013] &lt;br&gt;Leveraging in-space vacuum deposition and lunar resources to fabricate solar cells and transmission wire to create a powergrid on the surface of the Moon.</td>
</tr>
<tr>
<td>Ignatiev A., Sadoway D., Curreri P., Carol E.</td>
<td><strong>The Use of a Lunar Vacuum Deposition Paver/Rover to Eliminate Hazardous Dust Plumes on the Lunar Surface</strong> [#5014] &lt;br&gt;Based on available lunar resources and the Moon’s ultra-strong vacuum, a vacuum deposition paver/rover can be used to melt regolith into glass to eliminate dust plumes during landing operations and surface activities on the Moon.</td>
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<td>Yun P.</td>
<td><strong>Lunar In Situ Resource Utilization (ISRU) and Commercialization</strong> [#5122] &lt;br&gt;A feasible and sustainable lunar ISRU through commercialization can happen with affordable transportation and power supply. Lunar tourism can be a significant financial source for continued expansion of permanent human habitation on the Moon.</td>
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<td>Schingler J. K., Kapoglou A., Hubbard K.</td>
<td><strong>Common Pool Lunar Resources</strong> [#5124] &lt;br&gt;This article offers a conceptual framework for structuring a discussion of property rights regimes for the Moon.</td>
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<tr>
<td>Harmer G.</td>
<td><strong>Integrating ISRU Projects to Create a Sustainable In-Space Economy</strong> [#5128] &lt;br&gt;This abstract is for a poster showing how integrating all the various lunar ISRU projects can have a big impact on how much (if at all) they contribute to the formation of a sustainable in-space economy.</td>
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<tr>
<td>Lacerda M., Park D.</td>
<td><strong>A Comprehensive Risk Assessment of the Proposed NASA Lunar Orbital Platform-Gateway</strong> [#5129] &lt;br&gt;A comprehensive risk assessment of proposed NASA Lunar Orbital Platform Gateway. Study will use gateway hardware element and human operation risk characteristics to assess overall platform risk levels and risk matrix to mission proposed and occupants.</td>
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<td>8:15 a.m.</td>
<td>Sanders G., Neal C. *</td>
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<td>8:25 a.m.</td>
<td>Mandt K. *</td>
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<td>8:40 a.m.</td>
<td>Li S. *</td>
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<tr>
<td>8:55 a.m.</td>
<td>Sargeant H. M. * Abernethy F. Anand M. Barber S. J. Sheridan S. Wright I. Morse A.</td>
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<td>9:00 a.m.</td>
<td>Wood S. E. *</td>
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<td>9:05 a.m.</td>
<td>Gruener J. E. *</td>
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<td>9:10 a.m.</td>
<td>Hibbitts C. A. *</td>
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<td>9:20 a.m.</td>
<td>Rogers N. Villeneuve M. *</td>
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<td>Time</td>
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<td>10:00 a.m.</td>
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Lunar water ice and volatile deposits are critical resources for ISRU. These resources can be found outside of permanently shadowed regions, allowing for ISRU operations in sunlit regions on the Moon. |
The Lunar T-REx tethered CubeSat/SmallSat mission concept makes repeated low altitude measurements that could be capable of identifying magnetic signatures associated with economic mineralization at Nectarian-aged impact features. |
| 10:25 a.m.   | Carroll K. A. *                | *Lunar Surface Gravimetry for Finding Ore Deposits on the Moon* [#5041]  
Will valuable lunar resources be in the form of concentrated ore deposits, or widely dispersed through the regolith? If the former, standard exploration techniques may help find ore bodies. We discuss the use of gravimetric surveying for this. |
Terrestrial volcanic fields are analogs for the geologic conditions that will be encountered on the Moon. Seismic and magnetic data from these locations will aid in the geophysical characterization and locating of lunar resources in similar areas. |
<p>| 10:35 a.m.   | Zacny K. *                     | <em>Prospecting for Lunar Resources</em>                                    |
| 10:50 a.m.   | Sowers G. *                    | <em>Prospecting Workshop at Colorado School of Mines</em>                   |
| 11:00 a.m.   | <strong>Moderator:</strong> Neal C. <strong>Panelists:</strong> Gertsch L. Hurley D. Martin G. Acierno K. | <em>Panel Discussion: What Does a Lunar ISRU Prospecting Campaign Look Like?</em> |
| 12:00 p.m.   |                                | <em>Lunch</em>                                                             |</p>
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<td>1:30 p.m.</td>
<td>Trautner R. *  Barber S.  Carpenter J. Fisackerly R.  Houdou B.  Leese M. Rusconi A.  Sefton-Nash E. Zamboni A.</td>
<td>Development of the PROSPECT Payload Package for Subsurface Sample Acquisition and Analysis of Lunar Volatiles [#5004] ESA’s PROSPECT package on board the Russian Luna-27 lander will support the extraction and analysis of lunar surface and subsurface samples at a lunar near-polar landing site, and acquire data from additional environmental sensors.</td>
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<td>1:35 p.m.</td>
<td>Morse A. D. *  Abernethy F. Barber S. J.  Lim S.  Sargeant H. Sheridan S.  Wright I. P.</td>
<td>Mass Spectrometers for In-Situ Resource Utilisation [#5026] The Open University has a heritage of building small, less than 2 kg, mass spectrometers for lander packages. Continuing development aims to use the mass spectrometers for prospecting for lunar resources and for ISRU process monitoring.</td>
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<td>1:40 p.m.</td>
<td>Zacny K. *  Paulsen G.  Mank Z. Spring J. Chu P.  Bergman D. Sanasarian L.  Quinn J.  Smith J. Kleinhenz J.</td>
<td>TRIDENT Lunar Drill with PlanetVac Pneumatic Sample Delivery: A New Paradigm in Sample Acquisition and Delivery [#5059] We present an approach for sample acquisition and delivery to instruments for analysis. Sample acquisition is done using a TRIDENT drill, while sample delivery is performed using a PlanetVac pneumatic sample delivery.</td>
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<td>1:45 p.m.</td>
<td>Meyen F. E. *  Campbell A. Steiner T. J. III  Streetman B. J. Mario C. E. Steffes S. R.  Duda K. R.</td>
<td>Bringing Your ISRU Payload to the Moon: How Artemis-7 and Draper’s Vision-Based Navigation Get You There [#5080] This presentation discusses Draper’s Artemis-7 lunar lander and describes payload accommodations and vision navigation features that enable the deployment of ISRU payloads to the Moon.</td>
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<td>1:50 p.m.</td>
<td>Schieber G. L. *  Jones B. M. Orlando T. M.  Loutzenhiser P. G.</td>
<td>Experimental Study and Modeling of Gas Transport Within Regolith for Examining ISRU/Sampling Scenarios [#5034] Understanding gas transport for the extraction of water within regolith is a key step in the design of ISRU systems. This study considers gas transport at low pressure in the porous medium formed by regolith.</td>
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<tr>
<td>1:55 p.m.</td>
<td>Mantovani J. G. *  Vu B. T.</td>
<td>Chemical Effects on Surface Regolith Caused by a Lunar Lander’s Exhaust Plume During Descent and Landing [#5070] This presentation will discuss previous work conducted at NASA Kennedy Space Center that studied the potential surface contamination that can be caused by a lunar lander descending into a lunar cold trap area.</td>
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<td>2:00 p.m.</td>
<td>Botha P. W. S. K. *  Butcher A. R.</td>
<td>The Geometallurgy of Lunar Simulants and Apollo 16 and 17 Regolith [#5045] We utilize geometallurgical characterization techniques to study seven lunar simulants; two sized Apollo 16 drive tube samples; and two sized Apollo 17 drive tube samples (74002,181 and 74001,113) using QEMSCAN.</td>
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<td>2:05 p.m.</td>
<td>Patterson M. C. L. * Tucker J. Carpenter K. Parness A.</td>
<td><strong>Understanding Component/Materials Performance in the Lunar Environment [#5056]</strong>&lt;br&gt;A test environment that closely approximates the lunar surface has been established to characterize the wear and degradation mechanisms associated with components such as gear boxes, predict performance, and establish mitigation strategies.</td>
</tr>
<tr>
<td>2:10 p.m.</td>
<td>Mueller R. P. * Mantovani J. G.</td>
<td><strong>Geotechnical Properties of BP-1 Lunar Regolith Simulant [#5068]</strong>&lt;br&gt;An experimental program including particle-size distribution, microscopy observations using scanning electron microscope (SEM) images, density measurements, compressibility, and shear strength was performed.</td>
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<tr>
<td>2:25 p.m.</td>
<td>Chung T. * Yoo Y. Shin H.-S.</td>
<td><strong>A Lunar Surface Environment Simulator: Dirty Thermal Vacuum Chamber (DTVC) [#5038]</strong>&lt;br&gt;KICT is developing a space environment simulator containing a large amount of a lunar soil simulant for verification of ISRU technology. It is expected to contribute to improve the completeness and reliability of the developed ISRU technology.</td>
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<tr>
<td>2:25 p.m.</td>
<td>Keshtelyi L. * Williams C. F. Howard D. A. Crafford T. C. Meinert L. D. Hagerty J. Ridley W. I.</td>
<td><strong>Applying the USGS Resource Assessment Methodology to the Moon: Three Very Different Cases [#5030]</strong>&lt;br&gt;We examine the application of the standard USGS mineral resource assessment methodology to lunar ice, regolith, and solar energy.</td>
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<tr>
<td>3:00 p.m.</td>
<td>Cannon K. M. * Britt D. T.</td>
<td><strong>Mineralogically Accurate Simulants for Lunar ISRU, and Strategic Regolith Processing [#5002]</strong>&lt;br&gt;Beneficiating lunar resources will be controlled by properties of soils/rocks that are only captured by mineralogically accurate simulants. We describe two such regolith simulants and a distribution model that solves previous simulant issues.</td>
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<tr>
<td>3:30 p.m.</td>
<td>Johnson L. *</td>
<td><strong>Lunar Power Lander for Surviving Long Lunar Nights [#5001]</strong>&lt;br&gt;A Lunar Power Lander concept is presented that will utilize concentrated solar thermal radiation as an energy source for generating and storing electrical power during the day for use during lunar nights.</td>
</tr>
<tr>
<td>3:40 p.m.</td>
<td>Coyan J. A. * Schmidt G.</td>
<td><strong>Mineral Resources Assessments: Implications for Assessing Cosmic Bodies [#5092]</strong>&lt;br&gt;Resource assessments provide leaders a framework for making decisions under conditions of uncertainty. Three Part Mineral Resource Assessment Method may be applicable to assess resources on cosmic bodies.</td>
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<tr>
<td>3:45 p.m.</td>
<td>Ehrlich J. W. * Cichan T. Payne K.</td>
<td><strong>Advancing In-Situ Resource Utilization Through Current and Future Deep Space Technologies [#5067]</strong>&lt;br&gt;Lockheed Martin has a rich background in the design and testing of ISRU technology. Revitalization of previously proven technology, such as the Precursor ISRU Lunar Oxygen Testbed (PILOT), will allow NASA to press ahead in advancing ISRU at the Moon.</td>
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<td>Time</td>
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<td>3:50 p.m.</td>
<td>Colaprete A.* Elphic R. C. Shirley M.</td>
<td>Characterizing Lunar Polar Volatiles at the Working Scale: Going from ISRU Goals to Mission Requirements [#5025] This paper presents new geostatistical analysis and modeling to quantify critical parameter scales and mission requirements for adequate characterization of polar volatiles.</td>
</tr>
<tr>
<td>3:55 p.m.</td>
<td>Moderator: Boucher D. Panelists: Neal C. Sanders G. Abbud-Madrid A. On M.</td>
<td>Panel Discussion: What is Needed to Determine “Grade and Tonage” of a Deposit and How Does Bulk Regolith Characterization Play a Role?</td>
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<td>Just G. Smith K. Joy K. H. Roy M.</td>
<td>Parametric Review of Regolith Excavation and Handling Techniques for Lunar In Situ Resource Utilisation [#5007] Review of regolith excavation and handling techniques for lunar ISRU. To compare different mechanisms, representative parameters are chosen (process parameters and experimental conditions). Probability of incorporation into future lunar missions is evaluated.</td>
<td></td>
</tr>
<tr>
<td>Sargeant H. M. Bickel V. T. Honniball C. I. Martinez S. N. Rogaski A. Bell S. K. Czapinski E. C. Farrant B. E. Harrington E. M. Tolometti G. D. Kring D. A.</td>
<td>Determining Trafficability of Pyroclastic Deposits and Permanently Shaded Regions of the Moon Using Boulder Tracks [#5019] Pyroclastic deposits and permanently shaded regions are of interest for lunar ISRU. This work uses lunar boulder tracks to calculate the bearing capacity of regolith in these locations, and discusses the implications for future missions.</td>
<td></td>
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<tr>
<td>Mueller R. P. Smith J. D.</td>
<td>NASA Kennedy Space Center Swamp Works: Capabilities and Facilities [#5069] The Swamp Works is a KSC environment designed for innovation and lean development of new space technologies. It establishes rapid, innovative, and cost effective exploration mission solutions through leveraging of partnerships.</td>
<td></td>
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<tr>
<td>Baiden G. R. Barnhard G. P. Blair B. R.</td>
<td>Lunar Production Drilling Using WaterWitch [#5087] Improved technologies for lunar regolith processing mechanisms and end-to-end process flow engineering required for the recovery of resources and specific mechanisms for Lunar Regolith Processing (e.g., WATERWITCH).</td>
<td></td>
</tr>
<tr>
<td>Vaughn L. A.</td>
<td>A Modular Robotic System for In-Situ Extraction and Processing of Lunar Resources [#5094] An autonomous system of modular robotic components is described that is capable of excavation and transportation of materials between the various work centers of an operational or demonstration lunar mining, manufacturing, and construction facility.</td>
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Reaching great depths on the Moon for human’s settlement, ISRU, and construction of infrastructure applications will require effective drilling mechanisms, and this is the subject of this paper using a piezoelectric actuator. |
| Rhodes D. J.  Farrell W. M. | **Drilling in a Lunar Polar Crater: Triboelectric Charge Regulation** [#5119]  
We model the electrical environment of a lunar polar crater, and explore implications for drilling. Considerations include the plasma-surface interaction, tribo-electric charge buildup on equipment, and charged dust levitation. |
Here we describe the latest updates regarding lunar polar simulant development at JSC. In addition, we describe our ongoing effort to complete a lunar environment chamber, allowing high-fidelity testing of sample handling and volatile extraction. |
<table>
<thead>
<tr>
<th>Authors</th>
<th>Abstract Title and Summary</th>
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<tbody>
<tr>
<td>Indyk S.  Benaroya H.</td>
<td>Structural Members Produced from Unrefined Lunar Regolith Simulant [#5015] Evaluation of sintered lunar simulants structural properties with applications for lunar construction.</td>
</tr>
<tr>
<td>Elliott J. O.  Sherwood B.  Austin A.</td>
<td>Operations Modeling of ISRU Lunar Base Architectures [#5021] We present preliminary results of an operations-based model for an ISRU lunar base that takes into account all phases; construction through full operation. Architectural impacts are illustrated by comparing results from two different base locations.</td>
</tr>
<tr>
<td>Hanks H. L.</td>
<td>Prospective Study for Harvesting Solar Wind Particles via Lunar Regolith Capture [#5022] In this prospective study, a process to extract solar wind particles from lunar regolith is being designed to minimize required energy input by maximizing heat integration and utilizing existing hot and cold sinks and daily temperature variations.</td>
</tr>
<tr>
<td>Metzger P. T.  Britt D. T.</td>
<td>Mitigating Lander Plume Effects with Space Resources [#5055] Lunar lander plume effects must be mitigated to prevent damage to the operations at a lunar outpost or mining operation. Mitigating the effects require the use of lunar regolith as a construction material to build landing pads.</td>
</tr>
<tr>
<td>Whizin A.  Raut U.  Retherford K.  Miller M.  Poenitzsch V.  Kirkpatrick K.  Shin H.</td>
<td>In-Situ Synthesis of Propellants and 3D Printed Materials from Lunar Regolith [#5086] In order to enable operations and long-term human and robotic presence on the lunar surface, our work advances the science and technology required for scalable production in-situ building materials as well as propellants from lunar feedstocks.</td>
</tr>
<tr>
<td>Barnhard G. P.  Blair B. R.</td>
<td>Solar Dynamic Systems: A Path to a Lunar Power and Light Company [#5088] The ability to provide power when and where needed is essential to virtually all aspects of human endeavor and enables all forms of space development/settlement including lunar ISRU. Solar dynamic systems may prove integral to accomplishing ISRU.</td>
</tr>
<tr>
<td>Poston M. J.  Miller M. A.  Green S. T.  McElney A. B.  Retherford K. D.  Raut U.</td>
<td>Gas Storage Systems for In Situ Resource Utilization [#5091] Between processing and marketing, resources must be stored efficiently. We propose to study how.</td>
</tr>
</tbody>
</table>
### Methods of Heating Areas for Human Living Under the Surface of the Moon [5107]

At 1 m² of Moon’s surface from the Sun comes more than 1.3 kW of energy. This energy must be taken, transformed, transmitted under surface, there accumulated and to be used for heating of habitations.

### Comparison of Selected Lunar Regolith Simulants and Implications on their Potentials for ISRU-Related Applications [5123]

This study compared some simulants produced in different countries to show their strengths and weaknesses and commented on their potentials to serve ISRU technology development.

### Thermogravimetric Analysis of the Reduction of Ilmenite and NU-LHT-2M with Hydrogen and Methane [5125]

TGA was performed on ilmenite and NU-LHT-2M to study the weight change in a flow of nitrogen/hydrogen/methane from room temperature up to 1000°C. The feasibility of these ISRU processes at <1000°C was assessed and several challenges were identified.

### ispace’s Polar Ice Explorer: A Commercial ISRU Exploration Mission to the South Pole of the Moon [5126]

The topic of presentation will provide an update on the development of the lunar lander and rover and provide insight into the Polar Ice Explorer mission that is being developed.
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<tbody>
<tr>
<td>8:15 a.m.</td>
<td>Gertsch L. *</td>
<td><em>What is Mineral Extraction? What We’ll Be Hearing This Morning and How It Maps to Needs</em></td>
</tr>
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<td>8:30 a.m.</td>
<td>Ellery A. A. *</td>
<td><em>Sustainable Lunar In-Situ Resource Utilisation = Long-Term Planning [#5017]</em> We present a lunar industrial ecology that can be developed robotically on the lunar surface consistent with the Lunar Gateway to pave the way for a subsequent sustainable human presence on the Moon.</td>
</tr>
<tr>
<td>8:45 a.m.</td>
<td>Mueller R. P. *</td>
<td><em>A Review of Extra-Terrestrial Mining and Construction Concepts [#5066]</em> There have been a variety of extra-terrestrial robotic mining concepts proposed over the last 40 years, and this talk will summarize and review concepts to serve as an informational resource for future mining robot developers and operators.</td>
</tr>
<tr>
<td>9:00 a.m.</td>
<td>Williams H. * Dreyer C.</td>
<td><em>Space Resource Enabling Technology Development at the Colorado School of Mines [#5053]</em> At the Center for Space Resources in the Colorado School of Mines, key enabling technologies for lunar ice mining, regolith 3D printing, and in-situ geophysical investigation are being actively developed and will be reviewed in this presentation.</td>
</tr>
<tr>
<td>9:05 a.m.</td>
<td>van Susante P.J. * Alger R.</td>
<td><em>Proposed New Testing Facility for Cold and Operational Long Duration Testing of Lunar and Mars ISRU and Mobility [#5048]</em> Mining water and other resources from the Moon, Mars, and asteroids requires development and testing of mining equipment. We propose to develop a test facility for large scale, long duration ISRU testing under simulated lunar and martian conditions.</td>
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<td>9:10 a.m.</td>
<td>Metzger P. T. *</td>
<td><em>High Fidelity Model of Lunar Volatile Extraction Indicates Challenges and Solutions to Economic Resource Recovery [#5090]</em> Lunar modeling is developed for thermal extraction of models including the physics of heat transfer, ice sublimation, and gas diffusion, accounting for the effects of mixed chemistry ice in the soil. The model informs design decisions for mining.</td>
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<tr>
<td>9:15 a.m.</td>
<td>Goertzen S. G. * Conners A. B. Gregg R. Hugo A. Webb N. Hunter H.</td>
<td><em>Nuclear Power Demonstration in a Permanently Shadowed Region of the Moon [#5078]</em> The goal of this project is to develop a power demonstration system for use in a PSR on the lunar surface. Using nuclear fission reactors, this project will demonstrate power production for ISRU where sunlight is not readily available.</td>
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<td>9:20 a.m.</td>
<td>Stoica A. *</td>
<td><em>A Solar Power Infrastructure Around Shackleton Crater [#5096]</em> A solar power infrastructure around the south pole of the Moon could enable long term missions in regions without natural solar illumination. It could change the way missions are designed and operated, lower the barriers of entry, lower the cost of operation for exploration and ISRU.</td>
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<td>Townsend I. I. Tamasy G. J.</td>
<td>Dust Tolerant Umbilical to pass commodities such as cryogenic liquid</td>
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<td>propellants, purge and buffer gases, water, breathing air, pressuriz</td>
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<td>ing gases, heat exchange fluids, power, and data.</td>
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<td>9:30 a.m.</td>
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<td>Author Discussion Panel</td>
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<td>10:00 a.m.</td>
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<td>Break</td>
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<td>10:15 a.m.</td>
<td>Schuler J. M. * Smith J. D.</td>
<td>RASSOR, the Low-Gravity Excavator [#5061]</td>
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<td>Mueller R. P. Nick A. J.</td>
<td>Description of a robotic mining vehicle designed to operate in low-</td>
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<td>gravity.</td>
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<td>10:20 a.m.</td>
<td>Roesler G. *</td>
<td>Beyond Rovers: Mobility for Lunar ISRU [#5097]</td>
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<td>A mobility system for a production-level ISRU facility must provide</td>
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<td>efficient delivery, construction, resource transport, and robot po</td>
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<td>wer while mitigating extreme cold, abrasion, and obstacles. A robo</td>
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<td>tically-emplaced elevated track approach is discussed.</td>
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<td>10:25 a.m.</td>
<td>Morrison P. * Zacny K. Vendiola</td>
<td>Results and Lessons Learned from Testing of the Planetary Volatiles</td>
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<td>V. Paz A.</td>
<td>Extractor (PVEx) and Related ISRU Concepts [#5076]</td>
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<td>We present a novel method for water and other volatile extraction o</td>
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<td>n the Moon.</td>
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<td>10:30 a.m.</td>
<td>Keravala J. * Nall M. Beinhoff D.</td>
<td>How OffWorld’s Swarm Robotic Mining Architecture is Opening Up the W</td>
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<td>Pittman B.</td>
<td>ay for Autonomous Insitu Mineral Extraction — On Earth and Beyond [</td>
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<td>#5044]</td>
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<td>OffWorld is building millions of smart robots working on the human</td>
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<td>supervision on Earth and in space, turning the solar system into a</td>
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<td>habitable place for life and civilization. Enabling human expansion</td>
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<td>off our home planet.</td>
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<td>10:35 a.m.</td>
<td>Hopkins J. B. Murrow D. Wiens S.</td>
<td>Lockheed Martin’s McCandless Lunar Lander Capabilities for ISRU Mis</td>
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<td>W. * Linn T.</td>
<td>sions [#5063]</td>
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<td>Lockheed Martin’s McCandless Lunar Lander, selected for NASA’s CLPS</td>
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<td>program, is designed to provide the larger mass, volume, and powe</td>
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<td>r needed for ISRU prospecting rovers or pilot processing plants.</td>
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<td>10:40 a.m.</td>
<td>Zuniga A. F. *</td>
<td>NASA Lunar Development Lab Concept: A Leveled Partnerships Approach</td>
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<td>for Lunar Resource Extraction, Utilization, and Infrastructure Deve</td>
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<td>lopment [#5062]</td>
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<td>NASA Lunar Development Lab is a new concept to bring together acad</td>
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<td>emy, industry, and NASA in an accelerator environment to generate n</td>
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<td>ew design solutions and technologies for lunar resource extraction,</td>
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<td>utilization, and infrastructure development.</td>
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<td>10:45 a.m.</td>
<td>Austin A. Elliott J. O. Sherwood</td>
<td>Integrated Engineering Modeling of an ISRU Lunar Base [#5040]</td>
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<td>B. *</td>
<td>Lunar ISRU will be a complicated and complex endeavor involving man</td>
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<td>y unprecedented operations and systems. This document describes th</td>
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<td>e development of an integrated systems model to discern holistic i</td>
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<td>nterdependencies of ISRU operations scenarios.</td>
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<td>10:50 a.m.</td>
<td>Sibille L. * Saydam S. Tapia Cor</td>
<td>Modeling Tool for Lunar Mining Optimization and Resource Processing</td>
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<td>tez C.</td>
<td>Based on Geological Contexts [#5099]</td>
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<td>A novel comprehensive mining and materials processing model inte</td>
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<td>grates the specific geology of the targeted resource, as done in</td>
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<td>terrestrial mining industries to generate comparative operational r</td>
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<td>esults for a particular resource deposit on the Moon.</td>
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<td>10:55 a.m.</td>
<td>Authors Discussion Panel</td>
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</tbody>
</table>
| 11:15 a.m. | **Moderator:** Gertsch L.  
**Panelists:** Boucher D.  
van Susante P. J.  
Panel Discussion: *What’s Still Missing? Where are the Holes? (So We Can Plan to Fill Them!)* |
| 12:00 p.m. | Lunch                                    |
### PROCESSING OF RESOURCES

**1:15 p.m.** USRA Conference Center  
**Chairs:** Jerry Sanders and Diane Linne

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<thead>
<tr>
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<th>Authors (*Denotes Presenter)</th>
<th>Abstract Title and Summary</th>
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<tbody>
<tr>
<td>1:15 p.m.</td>
<td>Linne D. *</td>
<td>NASA Development Plans for Resource Processing for ( \text{O}_2 ) and Water</td>
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<tr>
<td>1:30 p.m.</td>
<td>Gruener J. *</td>
<td>Lunar Material-Minerals Primer for Oxygen Extraction</td>
</tr>
<tr>
<td>1:40 p.m.</td>
<td>Sanders J. *</td>
<td>NASA ( \text{O}_2 ) and Water Production Architectures for Early Reusable Lander</td>
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</table>
| 1:55 p.m.   | Meurisse A. *  Carpenter J.  | ESA Activities as Support to ISRU Technology Development [#5006]  
The European Space Agency is starting new ISRU activities in 2019. This talk will present the end-to-end terrestrial demonstrators currently under development for research purposes, and the ISRU demo mission planned for 2023. |
| 2:00 p.m.   | Townsend I. I. *  Mueller R. P. Tamasy G. J.  Nick A. J.  | Regolith Size Sorter and Hopper [#5075]  
Regolith size sorter for lunar regolith processing. |
| 2:05 p.m.   | Quinn J. W. *                | Electrostatic Beneficiation of Lunar Regolith; a Review of Previous Testing as a Starting Point for Future Work [#5074]  
Summary results of electrostatic beneficitation of lunar simulants and Apollo regolith, in lunar high-vacuum, are reported in which various degrees of efficient particle separation and mineral enrichment up to a few hundred percent were achieved. |
| 2:10 p.m.   | Lim S. *  Morse A. D.  Anand M. Holland A.  | Understanding of Microwave Heating Behaviour of Lunar Regolith and Simulants [#5047]  
We have designed an industrial bespoke microwave heating apparatus. This apparatus will allow a thorough experimental investigation of the sintering mechanism of lunar regolith/simulant in the cavity. |
| 2:15 p.m.   | Wingo D. *                   | Vapor and Plasma Phase Pyrolysis; A Key to Lunar Industrialization [#5098]  
The vacuum of the Moon allows Vapor Phase Pyrolysis production of metals and oxygen at much lower temperatures than here on Earth. |
| 2:20 p.m.   | Sibille L. *  Schreiner S. S. Dominguez J. A.  | Advance Concepts for Molten Regolith Electrolysis: One-Step Oxygen and Metals Production Anywhere on the Moon [#5100]  
Several integrated concepts were recently developed by our team to advance this remarkable technology into position for demonstration on the lunar surface. Laboratory tests have demonstrated production of oxygen from any lunar regolith composition. |
| 2:25 p.m.   | Sadoway D. *  Ignatiev A. Curreri P. Carol E.  | Regolith Extraction Through Molten Regolith Electrolysis [#5012]  
Molten oxide electrolysis can directly electrolyze regolith as received to produce pure oxygen at one electrode and a plurality of liquid metals at the other electrode, doing so without the need for any form of supporting electrolyte. |
<p>| 2:30 p.m.   |                              | Discussion: Processing of Lunar Materials |
| 3:00 p.m.   |                              | Break |</p>
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<th>Time</th>
<th>Authors</th>
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<th>Summary</th>
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<tbody>
<tr>
<td>3:15 p.m.</td>
<td>Utz R. C., Miller M. C., Pass S., Valdez T. I. *</td>
<td>Robust Electrolyzer for Lunar ISRU Applications [#5082]</td>
<td>Teledyne will discuss the development and testing of an electrolyzer that is compatible with lunar regolith-derived water sources.</td>
</tr>
<tr>
<td>3:20 p.m.</td>
<td>Hayes A. K. *, Ye P., Loy D. A., Muralidharan K., Potter B. G., Barnes J. J.</td>
<td>Additive Manufacturing of Lunar Mineral-Based Composites [#5009]</td>
<td>This work explores methods of incorporating lunar minerals into additive manufacturing. Regolith simulants were 3D-printed in conjunction with polymeric binders in concentrations up to 60 wt.% using Fused Deposition Modeling (FDM) and robocasting.</td>
</tr>
<tr>
<td>3:25 p.m.</td>
<td>Buckles B. C., Mueller R. P. *, Gelino N. J.</td>
<td>Additive Construction Technology for Lunar Infrastructure [#5077]</td>
<td>Developing a lunar economy will require a significant amount of infrastructure on the lunar surface. To do this, we will need to investigate automated construction technologies.</td>
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<tr>
<td>3:30 p.m.</td>
<td>Makaya A. *</td>
<td>In-Situ Resource Utilization for Construction and Hardware Manufacturing to Support Lunar Exploration — Developments at ESA [#5039]</td>
<td>An overview of completed and ongoing activities, funded by or conducted within ESA, will be presented, reflecting the development of technologies for the processing of lunar regolith, for construction and hardware manufacturing.</td>
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<tr>
<td>3:35 p.m.</td>
<td>Shafirovich E. *</td>
<td>Combustion-Based Methods for Construction on the Moon [#5081]</td>
<td>We will present the results of our studies on the combustion of lunar and martian regolith simulants with magnesium, as well as on the combustion joining of ceramic tiles made of a lunar regolith simulant.</td>
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<tr>
<td>3:40 p.m.</td>
<td>Moderator: Sanders J. Panelists: Linne D., Wingo D., Mueller R., Meurisse A., Buckles B.</td>
<td>Discussion</td>
<td></td>
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<tr>
<td>4:10 p.m.</td>
<td></td>
<td>Wrap-Up</td>
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<td>5:00 p.m.</td>
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<td>Adjourn</td>
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NASA Lunar Development Lab Concept: A Leveraged Partnerships Approach for Lunar Resource Extraction, Utilization, and Infrastructure Development
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Abstract ispace is a company whose vision is to expand and sustain humanity’s presence in space by utilizing resources available on the Moon. In order to accomplish this vision, ispace set a 3-step roadmap: (Step 1) technology demonstration, (Step 2) transportation and resources exploration, and (Step 3) resources utilization. With proven technologies and a solid understanding of the lunar environment and resources ispace will be ready to execute the processing and utilization of lunar resources. The topic of presentation will provide an update on the development of the lunar lander and rover and provide insight into the Polar Ice Explorer mission that is being developed. This mission goals are twofold, first to gain a better understanding of the occurrence and distribution of hydrogen on the Moon. Secondly, to obtain information regarding the environment on the lunar poles such as the geotechnical properties of the regolith and lander contamination, both of which will be valuable for oncoming in-situ resources utilisation (ISRU) missions.
INTEGRATED ENGINEERING MODELING OF AN ISRU LUNAR BASE. A. Austin, J. O. Elliott, and B. Sherwood, Jet Propulsion Laboratory, California Institute of Technology, (4800 Oak Grove Dr., Pasadena, CA 91109, alexander.austin@jpl.nasa.gov)

Introduction: The stage is set for sustained operations on the Moon. US Space Policy Directive 1 made this goal explicit: “the United States will lead the return of humans to the Moon for long-term exploration and utilization...” Long-term human activities on the Moon will need to “live off the land”, using local resources: ISRU (in-situ resource utilization).

While promoted in the literature for decades and widely accepted as a key objective, lunar ISRU will be a complicated and complex endeavor involving many unprecedented operations and systems; many architecture options have been proposed. Technology choices and programmatic considerations will need to be taken into account and balanced along with simple metrics like delivered mass, specific power, resources required, etc. Focusing on one or another subset of ideas and values guarantees sub-optimized results, or impractical or even invalid findings. Such analysis deficiencies cannot best serve a national decision environment that seeks velocity yet also real progress, serial successes, and cumulative capabilities. Very few prior studies have tackled synergistic design and analysis of the complete set of base elements and necessary operations.

Model-based Design Approach: JPL (Jet Propulsion Laboratory) is working to understand modern principles for practical lunar basing, and to discern holistic interdependencies of alternative ISRU operations scenarios for potential implementation over the next 20 years. An operations model under development integrates the performance of all base elements (ISRU systems, habitat, energy systems, mobility systems, landers and surface-basing infrastructure, siteworks including shielding, etc.). Our integrated modeling approach has many benefits including:

- Design methodology that starts “with the end in mind” (“steady-state” base operations) to inform relevant design decisions such as the base build-up sequence
- Systems model that captures interdependencies of the base elements to yield a holistic view of the integrated performance of the complete base architecture
- Adaptable model that can evaluate a wide range of point scenarios and ideas, including introduction of new base elements over time.

Our study’s model-based approach develops and exercises a flexible tool whose insights can guide architecture-level decisions. To enhance the capabilities, the authors invite system providers to provide current system performance data (ISRU techniques and elements, energy system architectures, lunar lander designs, etc.) for inclusion in the model.

References:
LUNAR PRODUCTION DRILLING USING WATERWITCH. G. R. Baiden, G. P. Barnhard and B. R. Blair, 1 CEO, Penguin Automated Systems Inc., Sudbury, Ontario, Canada, <gbaiden@penguinasi.com>, 2 XISP Inc., 8012 MacArthur boulevard, Cabin John, MD 20818 <barnhard@barnhard.com>, 3 NewSpace Analytics, Denver, CO.

Introduction: This paper will describe a collaborative partnership to define and implement improved technologies for lunar regolith processing mechanisms and end-to-end process flow engineering required for the recovery of volatiles and other resources (i.e., intended end products), a system-of-systems to implement said improved methodology (i.e., context), and specific mechanisms for Lunar Regolith Processing (e.g., WATERWITCH), which is a necessary element to accomplish the same.

This work is germane to the development of In-Situ Space Resource Utilization (ISRU) applications such as space-based rocket propellant production, oxygen and water production for space Environmental Control and Life Support Systems (ECLSS), lunar structure development, and space manufacturing from non-terrestrial resources.

Technical Concept: The end-product of this partnership is envisioned to be an instrumented scalable robotically compatible protoflight tool, with the necessary integrated process flow analysis support to allow for effective operation in the intended environment. The objective is to make the protoflight system available for accommodation on one or more anticipated lunar payload opportunities.

Based on successful testing in the lunar environment, the goal would be to create commercial opportunities for scaled systems executable as a public/private partnership between NASA and XISP-Inc in conjunction with its consortium partners.

Relevance and Alignment: The ability to successfully mine lunar regolith for volatiles and ice would provide the resources essential for economical operations and human lunar habitation. A ready supply of oxygen and water is essential for life. The secondary products associated with the preprocessed regolith may prove instrumental in facilitating construction and the further separation of metals and other elements.

XISP-Inc seeks to create public private partnerships to define and execute Technology Development, Demonstration, and Deployment (TD 3) missions to foster Cislunar space development, which aligns with NASA’s strategic goals for expanding capabilities and opportunities in space. The TD 3 missions are intended to leverage the rapidly evolving U.S. commercial space industry, as well as academia, non-profit organizations, other government agencies and/or laboratories, allied international government space agencies, exuberant billionaires, and other motivated individuals with specialized skills/resources in orchestrated efforts to rise to the challenge of creating a vibrant Cislunar development ecosystem benefiting both commercial and government use of space.

Commercial Impact: The public private partnership will focus on advancing commercially developed Lunar Regolith Processing & End-to-end Process Flow Engineering that can benefit both the commercial and government use of space.

The general availability of non-terrestrial sources of water and oxygen will be transformative with respect to Cislunar space development, both for propulsion purposes and for supporting human habitation requirements. The ability to provide a ubiquitous supply of non-terrestrial water and oxygen is essential for the cost effective support of human life, and preprocessing the regolith to make it more tractable to work with when and where needed is mission enhancing if not enabling for all aspects of Cislunar development.
LUNAR RESOURCE PROSPECTING.  S. A. Bailey, Deep Space Systems Inc., 8100 Shaffer Parkway, Unit 130, Littleton, CO 80127; steve.bailey@deepspaceystems.com.

Introduction: The resource rich polar regions of the moon present unique challenges and opportunities for anyone seeking to fully realize the benefits of lunar in-situ resource utilization. To obtain adequate knowledge about the target lunar resources to effectively exploit them requires a direct and sustained presence. Insights about lunar resources gained from orbit have greatly enhanced our understanding of the potential for ISRU at the moon, but that knowledge is not sufficient to fully justify the commitment of large financial resources to implement an ISRU based commercial and/or exploration campaign. What is needed is knowledge of location, quality, quantity and accessibility of the resources that can only be gained by on-site prospecting.

Successful prospecting operations on the surface of the moon demand unique solutions. Each location on the moon presents its own challenges to successful landing and surface operations which drives specific requirements for any system intending to operate there. Survival of lunar nights, lighting conditions, thermal environments, communications with Earth, etc., all drive requirements on the design of any solution. The polar regions of the moon present their own unique challenges to any visiting vehicle.

The Deep Space Systems lunar lander selected for NASA’s Commercial Lunar Payload Services catalog provides NASA and commercial entities with a system optimized for resource prospecting in the polar regions of the moon. Designed to take advantage of the unique solar and thermal environments associated with the lunar polar regions, the DSS lunar lander, equipped with its mobility option, is precisely the tool needed to establish the knowledge base necessary to commit to an ISRU based economy at the moon. This lighting round talk will describe the DSS lunar lander formulation process and the design it produced that is now an asset in the CLPS catalog.
AUTO-GOPHER-2 (AG2) – AUTONOMOUS WIRELINE ROTARY PIEZO-PERCUSIVE FOR DEEP DRILLING  
Yoseph Bar-Cohen¹, Mircea Badescu¹, Stewart Sherrit¹, Xiaoqi Bao¹, Hyoeng Jae Lee¹, Shannon Jackson¹, Brandon Metz¹, Kris Zacyn², Bolek Mellerowicz², Daniel Kim², Gale L Paulsen², ¹Jet Propulsion Laboratory, California Institute of Technology, (MS 67-119), 4800 Oak Grove Drive, Pasadena, CA 91109-8099, Phone 818-354-2610, yosi@jpl.nasa.gov, web: http://ndea.jpl.nasa.gov, ²Honeybee Robotics Spacecraft Mechanisms Corporation, Pasadena, CA

Introduction: Reaching great depths on the moon for human’s settlement, ISRU, and construction of infrastructure applications will require effective drilling mechanisms. The required drill has to meet mass, volume and energy consumption constraints and conventional technologies are limited in meeting them. To address the related challenges, a deep drill, called Auto-Gopher-2 has been developed jointly by the JPL’s NDEAA laboratory and Honeybee Robotics Ltd. The Auto-Gopher-2 is a wireline rotary piezo-percussive drill that combines breaking formations by hammering using a piezoelectric actuator and removing and collecting the cuttings by rotating a fluted bit. The hammering is produced by the Ultrasonic/Sonic Drill/Corer (USDC) mechanism that has been developed by the JPL team as an adaptable tool for many drilling and coring applications. The USDC uses an intermediate free-flying mass to convert high frequency vibrations of a piezoelectric transducer horn tip into lower frequency hammering of the drill bit. The USDC concept was used in a previous task to develop an Ultrasonic/Sonic Ice Gopher and then integrated into a rotary hammer device to develop the Auto-Gopher-1. The lessons learned from these developments were implemented into the development of the Auto-Gopher-2, an autonomous deep wireline drill with integrated cuttings management and drive electronics. Subsystems of this wireline drill were developed in parallel at JPL and Honeybee Robotics Ltd. The AG2 system was field tested by drilling in a consolidated gypsum formation and reached 7.52 meters deep. In this paper, we present the latest developments as well as the results of the laboratory and field tests.

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LUNAR RESOURCES: FROM FINDING TO MAKING DEMAND. D. C. Barker1, 1MAXD, Inc., P.O. Box 58915, Houston, Texas, 77258. donald.c.barker@att.net.

Introduction: The concept of using any space resources to offset launch, transportation costs from planetary gravity-wells as well as enhance and augment future human habitation is historically well considered and not much altered [1].

The Problem of Space Resources: The difficulty in initiating any space resource exploration or acquisition is bound by 1) finding resources that fulfill the mining industries historical definition of a Proved Reserve (weather mined by humans or robots), and 2) availability of users for said resources.

The first can be addressed by the development of a dedicated and well-funded exploration program that will establish the high fidelity requirements of the Proven Reserve definition. An evolving Planetary Resource Management System (PRMS) designed to guide exploration goals, architectures requirements has been proposed [2]. Its roots were derived from traditional and historical terrestrial petroleum industry requirements [3-5]. Such a resource exploration program cannot be the sequential, multi-year approach historically used in the planetary sciences community as this increases the likelihood of programmatic cancellation under current funding and programmatic philosophies.

The second condition is multifaceted, requiring many more synergistic components to be in place before needs can be established. Two common sales points in the space resource lobbyist community include propellant production and insitu human consumable needs. These users require additional drivers and have various constraints to becoming enacted. To have a propellant that would be needed by a large group of users requires instilling a hardware standardization regime in the space propulsion community (i.e. cryogenic propellant vs space-storable species), which highlight the inherent problems of scale as well as in-space storage and transportation. This choice potentially excludes the only extant commercial market currently in space – long-duration satellites.

To establish insitu human consumable needs requires the establishment of a viable human population off Earth. This condition is constrained by the fact that there is no current habitable destination for humans off Earth that would need sustaining from native resources (i.e. there is no destination – it must be constructed). Furthermore, the condition of getting humans to any such location is constrained by addressing the “why” of them being there in the first place. Presently, space exploration mindsets and efforts have strictly been in the pursuit of scientific exploration and on a very small scale. This driver is not sufficient impetus to ensure large, long-term, growing and permanent human populations off Earth; populations that would need insitu resources. A potential terrestrial analogue or example is found in the historical demographics and evolution of the McMurdo Antarctic station [6].

Illustrating the historical and present scientific communities mindset regarding human involvement is found in last year’s workshop determining lunar science landing sites. Beyond the scientific interests, acknowledging knowledge gaps for human participation only marginally address human needs and requirements, including surface operations (e.g., excavating, transporting, and roving) and habitability (i.e. radiation environment). And, no effort is made to determine exact resource (e.g., volatiles) volumes and then use that as the primary driver for site selection [7]. Community efforts remain singularly focused on the science. Ultimately, the ISRU component relating to human endeavors is necessary to insure that off Earth habitation is sustainable. It drives architecture and hardware design, operations and controls long-term costs. The determination of resource availability first must drive the selection of sites for human settlement.

Discussion: Like any island on Earth, all locations in space are limited by easily available native resources and outside resupply. The Moon has uniquely different conditions that will result in needs that may not be the same as other locations and needed technologies may not be transferable. This increases the unique costs for a given location and may also inhibit the development of other or follow-on goals (e.g., Mars).

The vast majority of engineers and scientists get motivated and excited by 1) bending metal (i.e. the design, testing and release of new toys), 2) the process of exploration and scientific discovery and 3) the receiving of a paycheck. Unfortunately, none of these directly address the question of “why” or engender long-term sustainable goals or designs. In order to take the space resources question beyond the speculation phase, a multifaceted change in philosophy, goals and means must be enacted. This includes the goal of establishing a human settlement that creates the destination based on more purposes than just doing scientific research (e.g., mining operations, growing a permanent settlement off Earth, tourism, etc., and then science). Such developments must be worked in parallel with a robust and dedicated exploration endeavor that will locate Proved Reserves of resources.

SURFACE-TO-SURFACE POWER BEAMING

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Introduction: The ability to provide power when and where needed is essential to virtually all aspects of human endeavor and enables all forms of space development/settlement. XISP-Inc seeks to deliver significant commercial value in the form of power (and ancillary services as applicable) to a growing number of customers interested in Cislunar applications.

I. Space Power Beaming & Ancillary Services

A. Goals and Objectives

This payload will demonstrate the ability of Space Power Beaming & Ancillary Services (SPB&AS) technology to be used to provide wireless utility services (e.g., power, data, communications, navigation, time, heat, etc.) to multiple clients/customers (C/C) in the lunar environment in a cost and resource effective manner.

B. Approach and Methodology

The integrated payload will consist of a frequency agnostic cognitive Software Define Radio transceiver with a phased array gimbaled switchable aperture, related control electronics and software with compliant interfaces, as well as the interface specifications/rectenna kits for C/C use. The payload will leverage the International Space Station based Space-to-Space Power Beaming commercial Technology Development, Demonstration, and Deployment (TD3) mission products (i.e., hardware, software, data, interface kits, and operational experience) to deliver a space qualified surface-to-surface compatible technology demonstration which will be mission enhancing/enabling for the upcoming lunar missions.

SPB&AS will make use of a combination of Radio Frequency and Optical frequencies optimized to meet C/C requirements. The C/C rectenna will be designed for accommodation as stand-alone deployable or conformal arrays or for incorporation into reflectarray designs accommodating photovoltaics, Rx/Tx antenna, rectenna elements, and RFID data logs.

The payload will be activated and deployed after landing. The transceiver will be quiescent until commanded to provide power & ancillary services to other deployed payloads (e.g., rovers, RFID impactors, distributed assay instruments, etc.) The phased array gimbaled switchable aperture, is an evolvable unit starting with a planar phased array, adding on a flush mounting gimbal when it can be accommodated, as well as tunable/switchable aperture elements based on C/C requirements. The payload will be designed to multiplex the unidirectional power beam with bi-directional ancillary services. The payload will accept available input power from the landing infrastructure and a command data stream, the payload will accept telemetry and instrument data from C/C and provide power, commands, navigation bits, and time as needed.

Payload delivery and integration can be supported as early as March 2020, with the ability to support subsequent incorporation as optimized infrastructure in future missions as warranted. The proposed payload has no landing site preferences other than line of site access to supported C/C.

Since the design elements of the payload will be based on Alpha Cube Sat and the SSPB mission flight test article both of which have a mass limit of 14 kg and a stowed volume of 6U. The payload will live within the other identified potential lunar lander accommodation capabilities. Placement of the payload and operational flexibility required by the C/C will likely impact the necessity of incorporating the add-on gimbal, special deployment equipment, and design of the switchable aperture elements. The payload will be optimized to meet the C/C requirements in a satisfactory and sufficient manner first with additional performance margin added as available resources permit.

C. Relevance to Lunar Surface Instruments and Technology Payloads

The availability of power and ancillary services (e.g., communications, data, navigation, time, etc.) is essential to most if not all aspects of lunar operations. The unbundling of space electrical power systems (i.e., separation of power generation, transmission, distribution, control, and loads) affords opportunities for redistribution of mass, overall volume, surface area, and complexity which can be mission enhancing/enabling. Accordingly, this work is directly relevant to Power Generation, Distribution, and Energy Storage, and supports all the other stated areas of interest for technology demonstrations.
SOLAR DYNAMIC SYSTEMS: A PATH TO A LUNAR POWER & LIGHT COMPANY  G. P. Barnhard\textsuperscript{1} and B. R. Blair\textsuperscript{2}, \textsuperscript{1}XISP Inc. 8012 MacArthur Blvd., Cabin John, MD, 20818 <barnhard@barnhard.com>, \textsuperscript{2}NewSpace Analytics, Denver, CO.

Introduction: The ability to provide power when and where needed is essential to virtually all aspects of human endeavor and enables all forms of space development/settlement. XISP-Inc seeks to deliver significant commercial value in the form of power (and ancillary services as applicable) to a growing number of customers interested in Cislunar applications. Solar Dynamic Systems are a form of space solar power technology that promises to be one of the few large-scale energy generation options that can scale to meet the growing electrical energy demand both for space and for terrestrial applications worldwide.

Leveraging NASA Solar Dynamic Technology Investments: The use of Solar Dynamic Systems (SDS) for power generation in space applications holds considerable promise with respect to life cycle cost (in comparison to photovoltaic sources), readiness, availability, and resiliency based on the technology development accomplished to date. As described in numerous NASA design documents and papers, “Solar Dynamic systems consist of a concentrator which collects and focuses solar energy into a heat receiver which has integral thermal energy storage. A Power Conversion Unit (PCU) based on the closed Brayton thermodynamic cycle removes thermal energy from the receiver and converts that energy to electrical energy. Since the closed Brayton cycle is a single phase gas cycle, the conversion hardware (heat exchangers, turbine, compressor, etc.) can be designed for operation in Low Earth Orbit, and tested with confidence in test facilities on Earth before launch into space”. This paper describes a public private partnership approach to leveraging the Solar Dynamic work that was accomplished (then LeRC) both in house and under contract as part of the Space Station Freedom program and to build on it to deliver 25 kW Solar Dynamic System commercial modules that could be applied to a number of Cislunar space applications, including as a power augment to the International Space Station (ISS) as it was originally intended. In addition, the ability to leverage the NASA Glenn work in creating the next generation of technologies for solar power generation and power management and distribution capabilities would be valuable.

Relevance and Alignment: The ability to provide power when and where needed is essential to virtually all aspects of human endeavor and enables all forms of space development/settlement. This partnership seeks to complete the SDS mission design in order to deliver significant commercial value in the form of power and ancillary services to a growing number of Technology Development, Demonstration, and Deployment (TD**3) mission customers interested in operating on and/or co-orbiting with the ISS as well as to lay the foundation for many Cislunar and lunar surface applications.

The TD**3 missions are intended to also leverage the rapidly evolving U.S. commercial space industry, as well as academia, non-profit organizations, other government agencies/laboratories, other government space agencies, exuberant billionaires, and other motivated individuals with specialized skills/resources in orchestrated efforts to rise to the challenge of creating a vibrant Cislunar development ecosystem benefiting both commercial and government use of space.

Commercial Impact: Having dispatchable and/or deployable space power systems that are modularized and scalable provides an unparalleled level of readiness and resiliency for a range of markets throughout Cislunar space (i.e., from LEO through to the surface of the Moon). The combination of the above as well as reduced piece count, increased durability, lower square footage area per unit of power generated, and robotic assembly/maintainability promise significant economy of scale with respect to power generation and distribution, expanding existing and creating new markets for space electrical utilities.

XISP-Inc was formed in order to create public private partnerships that define and execute TD**3 missions to foster Cislunar space development, which aligns with NASA’s strategic goals for expanding capabilities and opportunities in space. XISP-Inc is seeking to leverage NASA technical expertise, test facilities, hardware, and software to accelerate the development of the TD**3 missions and reduce the costs associated with their implementation and the use of the fielded technologies.
SUPPORTING ISRU MISSIONS THROUGH MISSION CONTROL SOFTWARE. M. Battleri, M. Faragalli1, E. Reidi, M. Cole1, K. Raimalwali1, E. Smali1, M. Vandermeulen1, and M. Azizi1, Mission Control Space Services Inc. (1125 Colonel By Drive, 311 St. Patrick’s Building, Ottawa ON K1S 5B6, Canada. melisa@missioncontrolsparceservices.com, michele@missioncontrolsparceservices.com).

Introduction: In the coming years there will be a paradigm shift in space exploration from government to commercial missions, which will include commercial in-situ resource utilization (ISRU) missions. Private companies will launch, land and deliver payloads to the lunar surface primarily for anchor government customers through programs such as NASA’s Commercial Lunar Payload Services (CLPS), Lunar Surface Instrument and Technology Payloads (LSTP) and ESA’s Lunar Exploration Campaign Science and Payload.

While early commercial flights will see small, single-use tele-operated rovers with limited autonomy used to deliver payloads and provide data to Principal Investigators (PIs), the resulting 2-week missions will be time- and operator-intensive and, ultimately, expensive to operate.

Although these rovers will be able to accomplish basic technical objectives, more autonomous behavior – such as terrain perception, path planning, control or data analytics – would reduce operator workload, enable more distributed ground operations, enable multi-rover collaborative prospecting missions, and increase the safety, yield and efficiency of ISRU rover or lander mission(s) [1,2,3,4]. Further, private companies will have economic incentives not only to make missions more efficient and productive, but to reuse software across multiple payloads and missions.

We foresee a growing and near-term demand for an easily accessible, on-demand mission control software that would provide geographically distributed operations for commercial space companies, mission and payload operators, and researchers.

Mission Control Software (MCS): Mission Control Space Services Inc. (Mission Control) is developing the Mission Control Software (MCS) to address emerging operations and autonomy needs in upcoming privately-led lunar ISRU (and other) missions. MCS is a cloud-based solution that enables operation of lunar spacecraft (e.g. payloads, rovers), while securely distributing data access and command responsibilities to any number of users involved in a mission. MCS would also allow operators to offboard certain guidance, navigation and control algorithms to the ground segment, enabling more autonomous behavior for computationally limited platforms [5], such as microrovers – where direct teleoperation is widely considered a baseline concept of operations [6].

Through this technology, Mission Control brings the Software-as-a-Service (SaaS) paradigm to space exploration and extends it by offering Mission-as-a-Service and Data-as-a-Service layers to the emerging market of service-based commercial lunar missions.

How MCS Supports ISRU Missions: MCS would have direct applications to ISRU characterization, prospecting, and extraction missions, which would make use of instruments to measure and verify the extent of potential resource deposits, determine the composition of/form these resources are in, and conduct resource extraction. Landed missions of this nature would likely involve rovers in different locations, which would in some cases need to converge on/travel to areas of maximum resource concentration. MCS would directly benefit these missions by providing improved guidance, navigation, and control capabilities, storage of pertinent data collected by science instruments and transmission to ground operators and science teams, and allow for data sharing across multiple rovers or landers, which could facilitate greater autonomous capability.

Examples of algorithms that will be deployed in MCS include the Autonomous Soil Assessment System (ASAS) that uses data in real-time to learn terramechanics models for non-geometric hazard prediction; the Skid Steer Optimizer (SSO) that can plan energy-optimizing maneuvers for skid steer vehicles; and the Intelligent Planner that uses predictive capabilities by ASAS and SSO to plan multi-objective path profiles that minimize hazards and energy consumption.

Commercial Involvement in ISRU Missions: In addition to directly benefiting ISRU missions, MCS is an example of commercial involvement in ISRU missions, and highlights one area of commercial interest around ISRU. This is an example of a commercial product/industry that can grow out of ISRU, and also support NASA’s plans for Gateway and human lunar landings in the latter half of the 2020s. Data storage/transmission and communication aspects of MCS could be just as relevant to human missions as robotic missions.

Using Terrestrial Volcanic Fields as an Analog for the Geophysical Characterization of Potential Lunar Resources

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Introduction: Terrestrial volcanic fields are excellent analogs for the geologic conditions that will be encountered on the Moon. Field sites such as the San Francisco Volcanic Field (SFVF), AZ and Lava Beds National Monument (LBNM), CA, can be used for the refinement of field techniques and data analysis methods for application to the future resource prospecting that will enable lunar habitation. Potential lunar resources may encompass processable materials such as volatiles and minerals, along with geologic structures such as lava tubes that can be found in terrestrial volcanic fields. The detailed geophysical characterization of these locations can be difficult though due to the small spatial variations in the characteristics of the near subsurface and potential difficulty with traversing through the regions. These issues can compound the uncertainties of the non-unique nature of geophysical analysis. Characterization of both the geologic near surface, as well as location accessibility will be key to successfully executing resource exploration missions on the lunar surface.

Study Region: Our field sites include both the SFVF, as well as the LBNM. The SFVF study site is a 50 km² area that is centered on the SP Crater cinder cone, and is part of the San Francisco Mountain stratovolcano complex. It is characterized by numerous cinder cone volcanoes, lava flows, rilles, and faults. [1] LBNM, encompasses a multitude of lava tubes, lava flows, and cinder cone volcanoes associated with the Medicine Lake shield volcano. The lava tubes range in length from a few meters to nearly 7 km, with diameters up to 20 meters. [2, 3]

Approach and Analysis: For the SFVF we are addressing two primary scientific problems. The first of these is the distinguishing of multiple overlapping lava flows in the upper 40 meters of the surface. The second is to attempt to correlate the alignment of cinder cone vents to local faults and possible magmatic propagation along these faults. For these problems, active seismic techniques were employed. Shorter, 115 meter long, geophone lines were used to obtain data for lava flow analysis, while longer, 1 km long, nodal seismometer lines were used to collect data on the deeper structure to search for faults and magma propagation. In addition, a swath of magnetic data was collected around each of the 1 km nodal lines in an attempt to search for magnetic anomalies that may indicate a magmatic intrusion [4, 5]. 2-D seismic Bayesian inversion analysis has resulted in discerning several layers and possible faults. In addition, the seismic data will be used to create probabilistic power spectrum plots of the background seismicity.

At the LBNM we have collected ground level magnetic data, as part of the TubeX project [6], to use magnetics to characterize the geomorphology and location of lava tubes. At this point the magnetic anomalies results appear promising for locating intact lava tubes found along large diameter tube complexes. Additionally, GPS located LiDAR data of the tube structure has enabled forward modeling to produce the expected ground magnetic signature of a large diameter lava tube for comparison to field data. [7] The next step is to extrapolate these results for identifying magnetic signatures of other lava tube complexes such as those possibly found on the Moon. However due to the non-unique nature of magnetic inversion analysis, confirmation of an intact lava tube will likely require coupling with other geophysical techniques such as ground penetrating radar, gravimetry, or seismic sounding [6].

Conclusion: We have collected both seismic and magnetic data sets to address various geologic problems. The data collected in these field studies can be used for the characterization of the material properties of the subsurface layers, as well as to envelope the geophysical conditions such as the probabilistic power spectrum of the seismicity and the magnetic variability. Additionally, seismic source requirements can be determined along with data resolution for both seismic and magnetic studies. All of these will need to be accounted for in the collection of data on similar features on the Moon. Therefore, using the data from these studies to characterize the geophysical and surface conditions will aid in the ability to successfully execute a lunar surface geophysical study.

AN EXISTING MARKET FOR LUNAR PROPELLANT - GTO ORBIT RAISING AS A SERVICE. N. J. Bennett1, 1School of Electrical Engineering and Telecommunications, University of New South Wales, High St, Kensington, NSW, 2052, Australia. nicholas.j.bennett@student.unsw.edu.au

Introduction: Every year approximately 120 metric tons of geostationary satellites are launched, this represents an existing market that could be serviced immediately by lunar propellant tugs.

A Financial Model: GTO orbit raising has large revenue and cost advantages over LEO orbit raising for a lunar propellant mine.

Earth launch cost per kg to GTO is more than double the cost to LEO, and high I_sp lunar LH2/LOX would be replacing a larger mass of low I_sp bipropellant. This allows the service to charge more, and insulates the business case from falling Earth launch costs.

Transporting propellant from the lunar surface to GTO requires less than half the propellant per kilogram of transporting to LEO. Orbit raising to GSO requires much less propellant from GTO than from LEO. This allows the lunar mine size to be greatly reduced, requiring a much smaller initial investment.

Higher prices and lower initial investment deliver higher returns and/or lower risk via overcapacity/redundancy.

Using a previously published financial model for a lunar polar mine [1] we show that, all else being equal, the GTO orbit raising case will produce rates of return on initial investment that are much higher than the LEO case, we found an internal rate of return around 50%, comparable to the returns for supporting large manned exploration campaigns. We validated delta-v with NASA’s General Mission Analysis Tool and performed sensitivity analyses to vehicle inert mass fraction and GTO apoapsis.

Operational Details: The service could be implemented as follows:

1. No orbital propellant depots. Standby tugs in PSRs form the bulk of the depot.
2. Around when the Moon is crossing Earth equatorial plane a tug launches from the lunar surface to LLO then does a TEI into and a near GTO orbit with inclination matched to a customer launch site.
3. The customer satellite launches to a GTO matching the tug line of apsides. Current launches target the line of apsides for eclipse conditions; the same constraint, different utility function.
4. The tug rendezvous and captures the satellite; either during the initial transit to apogee or on a subsequent orbit, potentially after some perigee raising.
5. The tug raises the satellite orbit and deposits it into its GEO “slot”.
6. The tug returns to the lunar facility. The flight plan is similar to Moon Direct. [2]

Business Advantages:

1. Satellites do not require any modifications, standardizations, or propellant transfer. Launch procedures remain almost unchanged.
2. The service could prove itself by rescuing / disposing of GEO satellites with launch / operational anomalies.
3. Early adopters do not need to trust the service; many can launch as they do now, but agree to pay for a partial orbit raising which will extend useful life.
4. All electric drive satellites can be on station, making revenue, months ahead of schedule, with extended life.
5. As reliability is proven there is an incremental satellite engineering pathway from under fueling through to the complete removal of the apogee propulsion system.
6. The mine can scale incrementally to extend support deeper into Earth gravity well or for large manned campaigns.

Looking Forward: Any water to LH2/LOX mine produces excess O2. Consuming all the LH2/LOX for LOX transportation could supply the excess LOX to GTO like highly eccentric Earth orbits for interplanetary vehicles using other fuels like CH4 or LNG, about 80% of the propellant mass. This provides a modest 20% revenue increase, but the market is potentially much larger.

Conclusion: GTO orbit raising is an existing business that could be serviced from lunar sourced propellant, so a close stepping stone on the way to using lunar resources to support larger endeavors.

References:

MARKETS FOR LUNAR ISRU PRODUCTS AND THEIR VALUE. Dallas Bienhoff, Cislunar Space Development Company, LLC, 8455 Chapelwood Ct., Annandale, VA 22003, dallas.bienhoff@csdc.space

Introduction: Lunar in situ resource utilization (ISRU) discussions usually focus on water for propellants. There are other products and other markets to consider. ISRU markets and product values are a function of lunar activity, the transportation architecture, market location and underlying assumptions. Markets and product value are defined for a reference scenario and compared with data from two other scenarios.

The reference scenario includes a permanent continuously inhabited lunar outpost supported by a reusable cislunar transportation architecture. Two personnel and two cargo missions per year service the lunar activity, reminiscent of NASA’s Exploration Systems Analysis Study [1] in response to the Vision for Space Exploration [2].

ISRU product values are defined in $/kg and normalized with respect to value in low Earth orbit (LEO) as a function of use location.

Markets: While propellant for transportation is the most discussed market for ISRU products, there are others: radiation shielding, micrometeoroid protection, life support, landing zone and habitat construction, paving, internal outfitting and local industry. These markets may be on the Moon, in the Moon’s vicinity, in LEO, on Mars transfer vehicles or in Mars orbit.

Lunar ISRU Products: Regolith is the easiest ISRU product to obtain; it can provide radiation and micrometeoroid protection, life support, landing zone and habitat construction, paving, internal outfitting and local industry. These markets may be on the Moon, in the Moon’s vicinity, in LEO, on Mars transfer vehicles or in Mars orbit.

Lunar ISRU Product Value: Given CSDC’s architecture and imbedded assumptions, the maximum value of lunar ISRU products on the Moon is $43K to $74K/kg for use on the Moon, $13K to $19K/kg for Moon departure propellant, $4K to $5K/kg for export to EML1 and $1K to $2K/kg for export to LEO. When normalized to launch cost to LEO, values are 9.5 to 16.4, 3.0 to 4.3, 0.8 to 1.2 and 0.2 to 0.3, respectively.

Lunar ISRU Product Value Comparison: ULA, in their Cislunar 1000 scenario, states they will buy propellant on the Moon at $0.5K/kg for sale in LEO at $3K/kg to beat current $4K/kg launch cost from Earth [5], or 0.125 times launch cost. From Spudis [6], Moon water is calculated to cost $25K/kg, or 6.25 times launch cost, before amortizing $88B set-up costs.

References:
EMERGING MARKETS FOR LUNAR RESOURCES.

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Introduction: Emerging terrestrial markets are built as early customers for products and services evolve into a robust commercial ecosystem. We are standing close to the threshold of an emerging Cislunar Marketplace as major aerospace firms contemplate orbital refueling and the potential reuse of space transportation systems. NASA not only understands the importance of emerging market dynamics on expanding the strength of the US space industrial sector, they have become willing and capable partners in the process. Indeed, the seeds for today’s successful partnerships were sown into the Space Act that created NASA in 1958. Elements within the civilian space agency have encouraged those seeds to take root and are currently nurturing their growth and maturation, anticipating a bountiful harvest. The enabling role of NASA and other government customers in making new markets cannot be understated.

An Emerging Cislunar Marketplace: The natural endowment underwriting the potential for locally derived commodities in the Earth-Moon system is substantial. An entire 8th continent worth of natural resources sits at the edge of Earth’s gravity well, waiting for the right combination of vision, capital and initiative to unlock its wealth. Combined with reusable upper stages and landers, a space-based supply of propellant has long been seen as the key that could enable access to much of the inner solar system. The recent confirmation of lunar polar volatiles provides an access point to a supply line of in-space propellant. Refueling can linearize the rocket equation, banishing its tyranny to more distant venues.

Space commerce in Earth’s orbit today just passed one third of a trillion dollars with business activities that includes communication, navigation and remote sensing [1]. This sphere of space commercial opportunities is currently under expansion, as innovations in additive manufacturing, satellite servicing, commercial space stations and related fields are being financed by industry and private investors. The potential for geometric economic rewards entice us toward a new golden age as humanity becomes a “multi-planet species” [2]. Combining the richness of space mineral and volatile resources with natural environments that offer extreme cold, ultra-high vacuum, microgravity and abundant solar energy offers access to industrial processes that could only be imagined by prior generations. A multi-billion dollar investment today could unlock trillions in new wealth [1].

Primary systems that are needed to enable this include reusable upper stages and landers, a local source of minerals and/or rocket fuel, and an industrial vision for what to do with those building blocks. All three are under commercial development today - now is the time to act. The resources of the future are waiting to be harvested and brought to market.

Propellant Markets: Supply of fuel and oxidizer to a transportation provider can being modeled as an emerging market opportunity, expanding the well-understood, high-value heritage space commerce applications [3]. Understanding and predicting propellant consumption will help choreograph and animate the business and exploration value to both public and private customers that lies dormant in the concentrated reserves of lunar polar ice. Due to recent movements in commercial space investment, the potential exists for both public and private customers for propellant. New markets could emerge at various locations on the lunar surface, one or more of the Earth-Moon Lagrange points, in lunar orbit and especially in high-traffic inclinations of low-Earth orbit (LEO). Due to its location at the edge of the gravity well, the energy required to lift payload from lunar surface and place it in LEO much lower than the equivalent energy required to lift the same payload from Earth - an effect that is amplified by aerobraking. In the long term, this engineering leverage will turn into economic advantage.

Other Commodities: Future customers could also benefit from the use of space resources beyond propellant, amplifying the economic leverage of a planetary surface production plant by adding new customers and applications. Byproducts are an important source of revenue for terrestrial mining activities. A rich set of value-added products and services are envisioned, with the potential to leverage future power and propellant production infrastructure investments to generate new income streams at low marginal cost as new customers arrive in Cislunar space.

THE GEOMETALLURGY OF LUNAR SIMULANTS AND APOLLO 16 & 17 REGOLITH. P. W. S. K. Botha1 and A. R. Butcher2, 1Hippo Geoscience (pieter@hippogeoscience.com.au), 2Geological Survey of Finland (alan.butcher@gtk.fi).

Introduction: We re-examine the mineral and physical characteristics of seven lunar simulants (NU-LHT-1M, OB-1, JSC-1, JSC-1A, JSC-1AF, FJS-1, MLS-1) previously reported by [1]; two sized Apollo 16 drive tube samples (64002,262 and 64001,374); and two sized Apollo 17 drive tube samples (74002,181 and 74001,113) using QEMSCAN (an automated Scanning Electron Microscope Energy Dispersive Spectroscopy tool). Specifically we investigate the range of mineral and glass assemblages, chemical composition and textures (including grain size, shape, and associations) on a size by size basis. The objective of the project was to assess the characteristics of lunar regolith with a view towards informing the design and manufacturing of lunar simulants, which are key for engineering design of mission hardware and assessing potential human health risks posed by lunar soil and dust.

Lunar Simulants: False-color mineral and phase maps show the wide range of assemblages and textures in the seven simulants that are likely to impact on simulant behaviour and requires consideration when choosing one product over another for testing.

Apollo 16: The mineral/phase abundance chart for sample 64001,374 indicates similar phase proportions for the largest three size fractions, apart from an anomalous amount of SiO₂ in the -75μm/+45μm fraction. The -20μm size fraction, which is likely to contribute most to dust formation, interestingly contains significantly more Ca-Al-Si and Ca-Mg-Al-Si Glass components compared to the larger size fractions.

Apollo 17: A map of a single particle from sample 74001,113 shows complex textures, including evidence for a crystallization front having formed during devitrification of a glass melt. The crystallization of olivine and ilmenite within the glass resulted in a modified glass composition in-between the mineral crystals.

Conclusions: The new data show the importance of both mineral-chemical and textural analysis of lunar material to augment simulant design and human health studies. Physical parameters such as particle size, shape, composition and density, which are commonly determined in geometallurgical terrestrial mining studies, are required to fully understand the beneficiation behaviour of lunar minerals of specific interest, including ilmenite.

Correlated Raman and Reflectance Spectroscopy for in situ Lunar Resource Exploration. D. M. Bower1, T. Hewagama1, N. Gorius2, S. Li3, S. Aslam3, P. Misra4, T. A. Livengood1 and J. R. Kolasinski5, 1University of Maryland College Park, College Park, MD 20742, dina.m.bower@nasa.gov, 2Catholic University of America, Washington, DC 20064, 3NASA Goddard Space Flight Center, Greenbelt, MD, 20771, 4Howard University, Washington, DC, 20059.

Introduction: A composite instrument combining Raman spectroscopy and reflectance spectroscopy will enable rapid, nondestructive, passive characterization of planetary surface materials to identify trace compounds without sample preparation. The Rapid Optical Characterization Suite for in situ Target Analysis of Lunar Rocks (ROCSTAR) is designed to search for minerals and volatiles in lunar materials using a combined package of time-resolved visible (VIS) 532 nm and near-infrared (NIR) 785 nm Raman, supported by near-Infrared/mid-Infrared (NIR-MIR) reflectance spectroscopy. ROCSTAR implements mature vibrational spectroscopy techniques to probe for chemical species of significance in lunar prospecting. Resource identification is critical to develop a viable long-term lunar exploration program enabling a continued human presence. ROCSTAR capabilities will enable rapid quantitative measurements on lunar surface materials while reducing the need for mechanical or thermal processing to evaluate water and metal contents. Water is a priority resource essential to life support, facility operations, and synthesizing fuels. Mineral-bound metals are important resource targets in regolith and mare basalts [1]. Lunar minerals ilmenite and pyroxene are known hosts of metals like Cr, Ni, Co, and Mn, and ilmenite in particular has been considered for Fe and O2 extraction [2][3].

Raman spectroscopy provides structural information to identify trace compounds, including minerals, in a matter of seconds. Raman spectroscopy has been used for decades to measure the composition of returned lunar samples and analog materials ([4][5][6] and references therein). Reflectance spectroscopy has a strong lunar mission heritage to build on, having been used for decades to evaluate the mineralogy of the lunar surface via remote measurements from orbital platforms like Galileo, Clementine, Lunar Prospector, and the Moon Mineralogy Mapper (M3) on Chandrayaan 1, as well as multiple Earth-based telescope measurements [7][8][9]. The two complimentary techniques, used together, ensure near-comprehensive identification and accurate characterization of lunar materials suitable for resource extraction.

Science and Technology Goals: Our main goal is to provide the means for in situ standalone identification of priority resource materials on the lunar surface with minimal power needs in an compact package. The architecture of ROCSTAR ensures adaptability to any mission platform, whether that be inside a lander/rover or extended on a robotic arm, or as a handheld device carried by astronauts. ROCSTAR can determine the composition, variety, and distribution of minerals, metals, and water with correlated spectroscopic measurements. These measurements are achieved by pointing ROCSTAR’s probe at a target at a distance of a few mm with sequential activation of MIR-NIR reflectance acquisitions followed by NIR-VIS Raman acquisitions, each for ~0.5 – 40s integration time (depending on the target material).

Figure 1 Preliminary Raman and reflectance data supporting the design of ROCSTAR; Raman measurements of multiple minerals in one lunar regolith sample under 532nm excitation and NIR measurements of basalts acquired in the laboratory with USGS data for reference.

Identifying Resource-rich Lunar Permanently Shadowed Regions. H.M. Brown, M.S. Robinson, and A.K. Boyd, Arizona State University, School of Earth and Space Exploration, PO Box 873603, Tempe AZ, 85287-3603 hbrown6@asu.edu

Introduction: Cold-trapped volatiles including water-ice in lunar Permanently Shadowed Regions (PSRs) are a high priority resource for future space exploration [1]. Rates of supply and burial, distribution, and composition of PSR volatiles are poorly understood. Thus, amplifying the need to identify high priority PSR targets for focused exploration [1].

Current PSR observations from remote sensing instruments utilizing bolometric temperature, neutron spectroscopy, radar backscatter, 1064 nm reflectance, far-ultraviolet spectra, and near-IR absorption indicate surface and/or buried volatile deposits [2-8]; however, results from these datasets are not always correlated. We compared these PSR observations [2-14] to identify sites that likely host volatiles (Table 1).

The 10 largest-by-area PSRs at each pole were selected for study as well as 35 other smaller PSRs with high scientific interest [10-13]. For these 55 PSRs we compiled observations from published works [2-14] and ranked them by volatile/resource potential (28 south pole, 27 north pole).

PSR Volatiles Ranking: For each PSR, each dataset [2-14] was categorized based on median and percent coverage values. Rankings are split into three categories: consistent with volatiles (3; blue), conflicting observations or ambiguous results (2; yellow), and no coverage or inconsistent with volatiles (1; orange).

Lyman Alpha Mapping Project (LAMP) rankings for the north polar area were decreased by 1 due to low signal-to-noise ratio (S/N) [7,11].

Lunar Orbiter Laser Altimeter (LOLA) reflectance and Mini-RF 13 cm and 4.3 cm radar Circular Polarization Ratio (CPR) values are positively correlated with steep slopes [5,6], making rendering rankings sometimes problematic. For PSRs with median slopes >16°, LOLA and Mini-RF CPR values were decreased by 1.

Low S/N and image resolution in many Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) PSR images [15,16] may contribute to no positive detections of permafrost landforms, blocks <5 meters, or surface frost. However, ShadowCam, a future orbital instrument aims to landform, blocks <5 meters, or surface frost. Howev-er, ShadowCam, a future orbital instrument aims to resolve this issue by providing high-resolution (1.7 meters/pixel) and high S/N (>100) PSR imaging [17].

Classification: Total Rank was derived from the sum of all ranked dataset categories for each PSR, with values ranging from 8 to 22. PSRs were classified by Total Rank: values >18 are considered consistent with volatiles, 13 to 17 are ambiguous, and PSRs with ranks <12 are considered inconsistent with volatiles. Dataset and total rank values are listed in Table 1.

### Table 1. Top 10 PSRs ranked consistent with volatiles based on 8 datasets: Diviner annual bolometric maximum temperature [1] and ice depth stability today [9] maps, LOLA 1064 nm reflectance [5], LAMP UV off/on band ratio [6], Mini-RF CPR [4], Lunar Exploration Neutron Detector (LEND) epithermal neutron flux [2], Lunar Prospector Neutron Spectrometer (LPNS) hydrogen abundance [3], M3 near-IR ice detections [7], and LROC NAC PSR imaging [13]. Categories are derived from dataset median values within each PSR. Total rank is the sum of dataset categories, assuming equal value of importance for each dataset. (*) indicate low S/N in the north pole dataset. These 11 PSRs were ranked 3 for the Diviner, LOLA reflectance, and LPNS datasets (not shown).

<table>
<thead>
<tr>
<th>Crater Name</th>
<th>Lon</th>
<th>Lat</th>
<th>PSR Area (km²)</th>
<th>Mad Slope (°)</th>
<th>LOLA Abundance</th>
<th>LAMP UV CPR</th>
<th>LEND Neutron Flux</th>
<th>LPNS Hydrogen Abundance</th>
<th>Diviner Max Temp</th>
<th>Total Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoemaker</td>
<td>45.3</td>
<td>-88.0</td>
<td>1079.5</td>
<td>8.6</td>
<td>Blue</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Blue</td>
<td>21</td>
</tr>
<tr>
<td>Haworth 1</td>
<td>307.9</td>
<td>-67.5</td>
<td>1072.9</td>
<td>9.2</td>
<td>Blue</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Blue</td>
<td>20</td>
</tr>
<tr>
<td>Faustini</td>
<td>94.1</td>
<td>-87.2</td>
<td>665.9</td>
<td>11.4</td>
<td>Yellow</td>
<td>Blue</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Blue</td>
<td>20</td>
</tr>
<tr>
<td>Sverdrup 1</td>
<td>216.5</td>
<td>-88.2</td>
<td>548.7</td>
<td>5.6</td>
<td>Yellow</td>
<td>Blue</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Blue</td>
<td>19</td>
</tr>
<tr>
<td>Cabeus</td>
<td>331.4</td>
<td>-84.5</td>
<td>353.0</td>
<td>10.0</td>
<td>Blue</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Yellow</td>
<td>19</td>
</tr>
<tr>
<td>Bechetdetsensky U 1</td>
<td>153.1</td>
<td>94.6</td>
<td>1072.2</td>
<td>9.2</td>
<td>Blue</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Blue</td>
<td>19</td>
</tr>
<tr>
<td>Malapert Mountain</td>
<td>329.2</td>
<td>-85.7</td>
<td>337.2</td>
<td>10.9</td>
<td>Yellow</td>
<td>Blue</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Blue</td>
<td>19</td>
</tr>
<tr>
<td>Haworth 2</td>
<td>317.1</td>
<td>-89.9</td>
<td>442.1</td>
<td>5.2</td>
<td>Blue</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Blue</td>
<td>19</td>
</tr>
<tr>
<td>Bechetdetsensky U 2</td>
<td>198.1</td>
<td>85.6</td>
<td>371.2</td>
<td>8.3</td>
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<td>Blue</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Blue</td>
<td>18</td>
</tr>
<tr>
<td>Shaler</td>
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<td>183.2</td>
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<td>Blue</td>
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<td>Yellow</td>
<td>Blue</td>
<td>18</td>
</tr>
<tr>
<td>Sverdrup 2</td>
<td>168.8</td>
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<td>88.6</td>
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<td>Blue</td>
<td>Yellow</td>
<td>Blue</td>
<td>Yellow</td>
<td>18</td>
</tr>
</tbody>
</table>

### Conclusion: Renewed interest in the Moon and recent water-ice detection in some PSRs [8] reinforces the need to identify high priority sites for lunar prospecting. The PSR Volatiles Ranking table summarizes detections from lunar polar datasets, which allows for interpretation of resource-rich sites. The PSRs with the highest potential volatile economic grade and tonnage include: Shoemaker, Haworth, Faustini, Sverdrup, and Cabeus craters. Of these PSRs, Shoemaker has the highest median dataset values and most positive detection overlaps, displaying evidence for both patchy surface frost and buried ice deposits.

With the existing datasets, determining volatile resource grade and tonnage is not possible, however our ranking of PSRs is a useful tool to guide future landed missions that can determine true resource potential (grade and tonnage).

### References:

ADDITIVE CONSTRUCTION TECHNOLOGY FOR LUNAR INFRASTRUCTURE. Brad Buckles\textsuperscript{1} Robert P. Mueller\textsuperscript{2} and Nathan Gelino\textsuperscript{2}, \textsuperscript{1}The Bionetics Corporation – Granular Mechanics and Regolith Operations Laboratory, \textsuperscript{2}NASA Kennedy Space Center - Granular Mechanics and Regolith Operations Laboratory.

Introduction: Developing a lunar economy will require a significant amount of infrastructure on the Lunar surface. Humans will need to rely heavily on ISRU technologies to develop this infrastructure. One of the ISRU system’s primary requirements will be to provide construction materials to build habitats, storage bins, landing pads, roads and other infrastructure.

One method of utilizing these ISRU derived construction materials is through Additive Construction, a method to “3D print buildings”. The Granular Mechanics and Regolith Operations (GMRO) laboratory at the NASA Kennedy Space Center has developed and tested an extrusion based process for additive construction.

Materials: Several materials have been tested for this process, including mixture of granular lunar regolith simulant (BP1) and various polymers. However, it was found that material strengths can be drastically improved by using glass fiber. The material compound currently being used is a 70\% basalt glass fiber and 30\% PETG mixture. Basalt glass fiber can be created on the moon by melting and drawing the lunar regolith into fiber. This could be an incredibly valuable material for construction and manufacturing on the moon. Polymer binders would be made available in the form of astronaut trash, or bioplastics created from crops and algae that will be necessary for a human presence on the moon.

It is also possible to eliminate the polymer binders from the additive construction process completely. By directly sintering granular material or drawn glass fiber, structures can be created in situ without the need for polymers. The GMRO lab has investigated this and is continuing to research this option.

Emplacement: The emplacement mechanism used for additive construction testing in the GMRO lab is a large industrial robot arm with a custom designed extruder and feed system mounted to the end effector. For use on the lunar surface, many different emplacement mechanisms can be evaluated. Some options include, gantry machines, mobile robotic platforms, boom arms, cable driven machines, and more. Many of these strategies have different advantages. For example mobile robotic platforms can allow for faster construction with multiple robots that work together and reach into more extreme terrain.
MINERALOGICALLY ACCURATE SIMULANTS FOR LUNAR ISRU, AND STRATEGIC REGOLITH PROCESSING. K. M. Cannon¹ and D. T. Britt¹, University of Central Florida, Department of Physics. 4111 Libra Drive, Physical Sciences Building 430, Orlando FL 32816. Email: cannon@ucf.edu.

Introduction: Regolith simulants have been in wide use since the run-up to the Apollo missions [1-3]. These materials are never perfect replicas of lunar soil, but serve as stand-ins to do basic science and to mature technologies for future exploration, especially ISRU.

Historically, the vast majority of lunar simulants (http://sciences.ucf.edu/class/planetary-simulant-database/) consisted of basalt ground into a powder. Almost all focus was put on the particle size and bulk chemistry. In a survey conducted of simulant users, only 14% stated modal mineralogy was an important property of a simulant [4]. Here, we argue that mineralogically accurate simulants are necessary to properly test ISRU technologies, particularly for high-energy processes to melt regolith, extract oxygen, and to create metals, ceramics, and composites.

Mineralogy and ISRU: The first stages of lunar ISRU will likely consist of moving regolith for radiation shielding, compaction to construct landing pads/roads, and extracting ice from polar regions. In most of these cases the granular mechanics of regolith are paramount, and low-fidelity simulants made from crushed basalt and anorthosite may be suitable in these cases. However, the next stages of ISRU will involve higher energy inputs and intensive processing to drive useful chemical reactions. Because minerals are the basic building blocks of planetary materials, the unique combination of minerals present in lunar materials will dictate their properties and behavior: this includes optical, magnetic, thermophysical, and chemical reactivity. Only mineralogically accurate simulants will be useful to properly develop, test, and validate technologies needed for advanced ISRU processes.

Mineral-based Simulants: The Center for Lunar and Asteroid Surface Science (CLASS) at UCF has absorbed the former Deep Space Industries regolith simulant operation and rebranded it as the Exolith Lab. The lab consists of a warehouse facility in Orlando where we are producing and distributing bulk quantities of regolith simulants as a not-for-profit effort. We have developed two root mineral-based simulants (Fig. 1), the Lunar Highlands Simulant (LHS-1) and the Lunar Mare Simulant (LMS-1). These are based respectively on the clean highlands soil 67461, and the clean mare soil 24999. We have also created a frozen volatile-bearing highlands simulant (FROST-Y) and a non-mineralogical silicate dust simulant (DUST-Y).

Fig. 1. LHS-1 and LMS-1 Lunar simulants.

Strategic Regolith Processing: Most ISRU processes will require filtering bulk regolith to separate out a particular particle size fraction or compositional component. What will be done with the unused parts? In addition to useful outputs, waste products are also produced: where will they go? We are developing a conceptual framework (Fig. 2) to chain ISRU processed together to extract the most value out of bulk regolith on the Moon, and are using our mineral-based simulants to test out segments of these processing chains with a series of experiments.

Fig. 2. Portion of the regolith processing framework.

LUNAR SURFACE GRAVIMETRY FOR FINDING ORE DEPOSITS ON THE MOON. K. A. Carroll, Gedex Systems Inc., 407 Matheson Blvd. East, Mississauga, Ontario, Canada L4Z 2H2, kieran.carroll@gedex.com

(Abstract for a 5-minute Lightning Talk.)

Many valuable natural resources on the Earth are found in ore deposits: rock containing a high enough concentration of the desired material, in a form that is amenable to refining, as to make it economical to extract it. It is an open question as to whether this will also be the case for economically viable deposits of resources on the Moon. That rather depends on markers developing for lunar resources, which is speculative. Consider, for example, water as a Lunar resource. Water in the form of ice deposits in permanently shadowed polar regions may be particularly localized in some parts of such PSRs; or, perhaps every shovelful of dirt from a PSR will have about the same concentration of water in it, as every other shovelful.

On Earth, explorers for natural resources have developed numerous tools and techniques for finding likely locations for various types of ore deposits --- in a word, for Prospecting. Should some valuable Lunar resources be located in concentrated ore deposits, then existing terrestrial prospecting techniques may be useful for finding them.

One well-established and widely-used geophysical prospecting technique on Earth, is ground gravimetric surveying --- using a sensitive gravimeter instrument to make measurements of variations in surface gravity, along a traverse line or over a survey area, due to variations in density of subsurface rocks. With the development of Gedex’s VEGA instrument (an absolute vector gravimeter developed for use in space, suitable for operation aboard small robotic Lunar rovers), it is now possible to employ that technique on the Moon’s surface. Some possible examples of Lunar ores that could exhibit a detectable density response are water ice, and ilmenite (another possible feedstock for producing oxygen and water on the Moon).
Integrated Analysis Framework for Space Propellant Logistics: Production, Storage, and Transportation
H. Chen1, T. Sarton du Jonchay1, L. Hou1 and K. Ho1, 1University of Illinois at Urbana-Champaign, Department of Aerospace Engineering, Talbot Laboratory, MC-236, 104 South Wright St, Urbana, IL 61801, kokiho@illinois.edu.

Introduction: As the interest in large-scale human exploration increases, in situ resource utilization (ISRU) attracts more and more attention for its long-term benefits in space transportation. However, traditional ISRU trade study models tend to only focus on ISRU plant design and do not capture its interaction with other space transportation systems. Our research proposes an integrated ISRU evaluation framework through the network-based space logistics architecture. It analyzes the performance of ISRU by considering plant deployment, regular production operations, and storage of the produced resource. The proposed framework can help the community identify the necessary infrastructure and its impact on architectures, to maximize the value of ISRU and identify technology gaps that need to be addressed to achieve those missions.

Literature Review: Past ISRU studies mainly focused on the architecture designs and their productivities. Schreiner [1] and Meyen [2] from MIT performed thorough analyses of ISRU performance, respectively. Lockheed Martin [3] and NASA [4] built their testbeds to evaluate the performance of ISRU. However, these studies did not consider ISRU plant deployment and propellant storage as part of the trade space. On the other hand, there are studies that considered ISRU plant sizing and space mission planning concurrently. Ishimatsu [5], Ho [6], and Chen [7] proposed a series of space logistics optimization frameworks based on the generalized multi-commodity network flow model (GMCNF) to optimize space mission planning together with the architecture design. However, their work considered the ISRU system as an integrated system and did not consider the tradeoff among ISRU subsystem sizing (e.g., reactor, power system, and storage) and their logistics.

Mathematical Framework: This paper proposes an integrated ISRU analysis and design framework through the network-based space logistics optimization model, as shown in the figure. In the network model, nodes represent planets or orbits; arcs represent space flight trajectories. The space transportation and logistics are denoted as commodity flows along arcs. Each subsystem of the ISRU plant is considered as a separate commodity. A large-scale multi-mission lunar exploration campaign will be considered as a case study. Multiple types of ISRU system will be evaluated from the subsystem-level focusing on the propellant production, storage, and transportation from the perspective of the space logistics. Our method can not only evaluate the productivity performance of an ISRU system, but also provide an effective subsystem sizing and technology selection tool that takes into account the plant deployment, ISRU production storage, and power supply.


Acknowledgments: This material is based upon work supported by the funding from NASA via the NextSTEP-2 ISRU award. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of NASA.
As plans for commercial utilization of lunar resources (both in cooperation with governments and in purely private sector activities) progress, those plans have resulted in considerable discussion of the legal and policy context at the multilateral and international level (as well as in context of national policy and regulation) A supportive policy and legal environment – that is consistent with key tenants and principles of international space law – will be an important element of developing a functional market for lunar resource use.

This lightning talk will discuss the importance of elucidating, describing, and sharing benefit(s) from space resources development with the broader space community (beyond those entities directly participating in any space resources activity) as a key element of achieving a supportive policy context for development of an in-space economy based on lunar resources utilization.

The Hague International Space Resources Working Group has published 19 policy and legal “building blocks” to support and enable the policy environment for space resources development. One of these building blocks focuses exclusively on benefit-sharing types and methods, identifying a number of potential benefit sharing approaches and outcomes which do not rely upon monetary benefit-sharing. The recently-released Commercial Lunar Propellant Architecture Study also identifies a number of benefits arising from lunar resources development and recognizes the important of this topic in the policy context.

The author is a member of the Hague International Space Resources Working Group and the author’s organization is a founding partner of the Working Group. The author also serves as Chair of the Working Group’s SocioEconomic Panel which seeks to foster dialogue and cooperation between governments, industry, international organizations, academia and civil society on socio-economical aspects of space resources activities; and to identify socio-economical challenges and benefit related to the use of space resources.
Introduction: A space environment simulator for the lunar surface is very helpful in developing ISRU technology available on the Moon. We can verify the technology in a more similar conditions to the actual lunar surface environment, which not only improves the reliability of the technology, but also increases the probability of mission success. The lunar surface is covered with rough and fine lunar soil known through the Apollo mission. Since ISRU is closely related to the lunar soil covering most of the lunar surface, a thermal vacuum chamber with lunar soil can be quite effective in developing ISRU technology. The Korea Institute of Civil Engineering and Building Technology (KICT) is developing a Dirty Thermal Vacuum Chamber (DTVC) containing a large amount of a lunar soil simulant for verification of ISRU technology on the moon. The DTVC, with an internal volume of 50 m$^3$, can be used to verify the full-scale ISRU equipment, which will improve the completeness and reliability of the developed technology.

Pilot DTVC: a pilot DTVC, with an internal volume of 1 m$^3$, has a similar configuration to the DTVC. The pilot DTVC is designed for technical verification and operation procedure development to be applied to DTVC. When the chamber is pumping down with soil, soil boiling or soil disturbance phenomenon occurs. To prevent this, the evacuation rate should kept below a certain value [1]. We have applied devices to adjust the evacuation rate of the chamber and are studying the optimal pumping down rate to prevent soil disturbance. We are also studying on soil pre-conditioning procedure to reduce time to reach the target pressure of the chamber by reducing the outgas from the soil.

DTVC: KICT is the process of constructing a large-scale lunar surface environment simulator based on the technology and experience obtained from various experiments using the pilot DTVC. The DTVC is in the form of a mailbox with inner dimensions of 4m (W) × 4m (H) × 4m (D). The main processing chamber was manufactured at the end of 2017, and thermal shrouds and heating lamp will be added to the main processing chamber in 2019. The DTVC is capable of creating under 10$^{-4}$ mbar pressure, -190 ~ + 150 °C temperature with 25 tons of soil. The DTVC is expected to be available for a rover’s driving testing, drill testing, regolith sintering testing, and various ISRU technology verification since its completion in 2020.

LUNAR FLASHLIGHT: SEARCHING FOR ACCESSIBLE WATER FROST. B. A. Cohen1, P. O. Hayne2, B. T. Greenhagen3, D. A. Paige4, C. A. Seybold5, J. D. Baker6; 1NASA Goddard Space Flight Center, Greenbelt MD (barbara.a.cohen@nasa.gov), 2University of Colorado, Boulder CO; 3JHU Applied Physics Laboratory, Laurel MD, 4UCLA, Los Angeles, CA; 5Jet Propulsion Laboratory, Pasadena CA.

Introduction: Lunar Flashlight is a very small satellite (6U bus, or 12x24x36 cm) developed and managed by the Jet Propulsion Laboratory that will search for water ice exposures and map their locations in the Moon’s south polar region. The Lunar Flashlight mission will demonstrate technologies for NASA such as green propulsion and active laser spectroscopy while proving the capability of performing a planetary science investigation in the CubeSat form factor. Lunar Flashlight was selected in 2014 by the NASA Advanced Exploration Systems (AES) program within the Human Exploration and Operations Mission Directorate (HEOMD); the mission is currently funded as a technology demonstration mission within NASA’s Space Technology Mission Directorate (STMD) portfolio. Lunar Flashlight will be one of 13 secondary payloads launched on the first test flight (EM-1) of the Space Launch System (SLS), currently scheduled for 2020 [1].

Polar water deposits: Near the poles of the Moon, permanently shadowed regions (PSRs) may hold a record of volatile delivery, transport, sequestration, and loss through geologic time [2-3]. Trapped water could be an important target of in situ resource utilization (ISRU), for life support or fuel and propellant [4-6]. Lunar polar water ice consists of two reservoirs: deeply buried ice deposits, and surficial water frost. The Clementine, Lunar Prospector, and Lunar Reconnaissance Orbiter (LRO) missions made observations consistent with ice deposits cm- to meters-deep with ~1% H2O by mass [7-10], but not all PSRs contain ice signatures. LCROSS revealed 5-7 wt% of H2O in the upper few m at Cabeus, along with a comet-like array of volatiles [11]. At the lunar surface, LRO and the Moon Mineralogy Mapper (M3) data are consistent with water frost at concentrations ranging from ~0.1 up to ~10 wt% with a patchy distribution [12-14]. However, the distribution of apparent water frost does not match the subsurface distribution, and neither is its occurrence proven everywhere temperatures are cold enough to permit trapping of water molecules [15]. Current data are not yet sufficient to conclude the form, quantity, or distribution of lunar H2O at concentrations sufficient for in-situ resource utilization (IRSU), or to predict the distribution of ice at scales of a rover or human landed mission. To be “operationally useful” for such missions, H2O concentrations of greater than ~0.5 wt% are required [16].

Lunar Flashlight measurements: The Lunar Flashlight mission will make definitive detections of surficial water frost within PSRs if it is present in quantities above ~2 wt% in areas measured by the mission. The Lunar Flashlight illumination system uses stacked laser diode bars to emit energy pulses at four near-IR wavelengths diagnostic of water ice in rapid sequence, while a receiver system detects the reflected light [17]. Derived reflectance and water ice band depths will be mapped onto the lunar surface to identify locations where H2O ice is present at the scale of ~10 km along-track, and about 30 m cross-track. In order to increase the SNR, the measurements can be added along-track to create the desired mapping resolution (~10 km). The total duration of laser firing per pass will be approximately 2-3 minutes during closest approach over the South Pole, potentially mapping the interiors of Shackleton, Shoemaker, Haworth, and Faustini craters. By repeating these measurements over multiple points, Lunar Flashlight will create a map of surficial water frost concentration that can be correlated to previous mission data and used to guide future missions. All calibrated data and derived data products will be publicly archived in NASA’s Planetary Data System (PDS).

Synergy with other missions: Two other missions on EM-1 (Lunar IceCube and LunarH-Map) will make complementary lunar volatile measurements [18-19]. Although each mission uses a different design and measurement approach, the results from these missions will be synergistic as a fleet of missions simultaneously exploring the nature and distribution of water on the Moon ahead of human exploration.

CHARACTERIZING LUNAR POLAR VOLATILES AT THE WORKING SCALE: GONG FROM ISRU GOALS TO MISSION REQUIREMENTS. A. Colaprete, R. C. Elphic, M. Shirley, NASA Ames Research Center, Moffett Field, CA, anthony.colaprete-1@nasa.gov

Introduction: The economic evaluation of natural resources depends on the accuracy of resource distribution estimates. A frequently discussed lunar resource is water ice, however, we currently do not have a sufficient understanding of the distribution of water or its forms at the scales it would be extracted and processed. This paper provides an analysis of the number and distribution of observations needed to guide the next steps in lunar water ISRU. We use a combination of Monte Carlo studies and geostatistical approaches to go from the exploration goal of “understand the distribution of water” to a quantification of specific mission sampling requirements.

The Need for Mobility and Subsurface Access: A number of existing data sets suggest that water ice is heterogeneous at scales down to meters. For example, to reconcile the LCROSS observed water concentrations of ~5% [1] with the observations of neutron counts the water would need to be either buried under a desiccated layer of regolith 20cm to 50cm deep and/or mixed laterally with an areal density of 20-40% [2]. These ranges of values for the lateral and vertical distributions are consistent with what one would expect due to the constant excavation/burial by impacts [3]. The distance between 10 m wide craters (~1 m deep) is ~50-150 m, consequently the top ~meter is likely to be patchy at scales of 10s-100s of meters. Modeling and geostatistical analysis can be used to better quantify the scales needed to be measured and the minimum number of measurements required to adequately characterize an area.

Geostatistics and Monte Carlo Modeling: The application of geostatistics in resource characterization dates back to the late 1970s and are useful for site assessment where data is collected spatially [4]. These same techniques can be applied to lunar spatial data sets and / or model predictions to evaluate the geospatial distribution of key physical parameters, including for example, surface and subsurface temperatures.

Variograms: One way to look at the lengths scales associated with the distribution of water is to generate variograms of the subsurface water ice stability depth (the depth at which subsurface temperatures are cold enough to retain water ice for extended periods). A variogram provides a measure of the spatial correlation of a given parameter. Figure 1 shows several variograms (each with the same origin but differing directions) calculated for an ice stability map near the north pole crater Hermite-A. The points at which the curves flatten represents a loss in autocorrelation between the parameter and distance (or lag), and are indicative of critical physical scales.

Monte Carlo Modeling: In addition to geostatistical analysis, Monte Carlo modeling of surface traverses has been carried out. The model generates maps of randomized water distributions with variable burial depth and concentration. For each model run “samples” are taken along a prescribed traverse path. These samples are used to estimate the overall average water concentration and variability and compared to the actual average concentration and variability calculated for each run. The difference between the estimates from just the samples and the actual values represents the error in the traverse sampling. These estimates can be used to derive mission requirements for the necessary rover traverse distances and sampling density. These estimates were made for a binary water presence (either the water was sensed or it was not). The next set of calculations applies instrument models for how they would actually sense the water (or hydrogen) along the traverse. Finally, simulated subsurface sampling can be added to better understand how the number of subsurface “tie-points” reduce the overall uncertainty in the estimates.

An exploration architecture for the Moon and Mars.
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Introduction: The aim of this presentation is to provide a thoughtful roadmap for a focused mars and moon exploration campaign integrating robotics, human and commercial activities. The goal is to minimize the influence of the territorial fiefdoms of NASA centers and congressional districts and determine the most efficient path forward to the moon and mars. This is intended to be achieved by first laying out an outline of the whole spectrum integrated activities from initial resource characterization to commercial exploitation. Then, once that is established, drawing on NASA centers of excellence and corporate sponsors/partners to achieve those goals. Simplicity and efficiency is the overall goal from a business as well as a systems engineering standpoint.

Simplicity and commonality between both the Lunar and Martian hardware is to be maximized. Potential use of 3D printed (earth/orbital/lunar or mars surface) components will be explored. Commonality and standardization between systems is also to be maximized and dead end single use or unique components are to be avoided. In other words the parts list should be as small as possible, with common fasteners, connectors, and interfaces wherever possible. As such, repair and cannibalization of hardware will enable more robust operations and simplify the logistics stream.

Introduction: Resource assessments provide governments and institutional leaders a framework for making decisions under conditions of uncertainty by supplying information about resources in terms of potential occurrence, distribution, type, quality, amount, value, and certainty in assessment results [1]. Mineral resource assessments include a variety of approaches, from qualitative techniques that identify favorable areas for the occurrences of resources to quantitative techniques that calculate probabilistic estimates of in-place resources. Qualitative resource assessments are expressed in the form of maps with prospective areas rated as high-medium-low, or on a unitless numerical scale for the predicted occurrence of a resource. Qualitative resource assessments provide a solution for regions that have insufficient data to conduct a fully quantitative assessment [2]. Quantitative assessments, such as the Three-Part Method, incorporate information that includes 1) permissive tracts, 2) resource grade and tonnage (quality and quantity) models, and 3) estimates of the number of undiscovered deposits (Figure 1) [1]. As a compromise between quantitative and qualitative resource assessment approaches, a semi-quantitative assessment can incorporate quantitative statistical data where appropriate as well as qualitative input such as expert observations and opinions.

Depending on the amount and type of data available, the nature of the deposit, and accessibility to analogue data, the Three Part Method may be applicable to assess resources on cosmic bodies. The Three Part Method is a USGS developed, well-established, quantitative method of estimating undiscovered resources. The Three Part Method has been successfully applied at the local and global scale to numerous commodities (see minerals.usgs.gov/science/assessments.html). The Three Part Method leverages a Mineral Deposit Model (MDM), which is a collection of information gathered in and around known deposits, and discriminates 1) possible mineralized environments from those that are barren, 2) types of known deposits, and 3) mineral deposits from occurrences. MDMs are composed of the essential attributes that describe a deposit type rather than a single deposit and include information such as mineralogy, alteration, geochemical, and geophysical anomalies [1]. The MDM directly informs delineation of Part 1, permissive tracts (mineral resource maps that delineate areas of favorable features/characteristics that are associated with the occurrence of a resource) and Part 3, estimation of the number of undiscovered deposits (Figure 1) [3].

Grade and Tonnage models (Part 2) consist of frequency distributions of tonnage (mineralized-bearing material) and average grade (quantity of mineral contained within a unit weight of mineral-bearing material) for analogue deposits (i.e., deposits that have been identified as belonging to the same MDM). They are populated from data collected from well explored areas and are used as one input into the Three Part Method [1].

![Figure 1: Three components of the quantitative Three Part Mineral Resource Assessment](image-url)

PRELIMINARY TRADE STUDY OF POWER GENERATION AND TRANSMISSION FOR LUNAR PROPELLANT MANUFACTURING. D. C. Dickson¹ and R. J. Centers², ¹,²Colorado School of Mines (1500 Illinois St., Golden, CO 80401, ddickson@mymail.mines.edu, centers@mymail.mines.edu)

Introduction: The production of propellant from volatiles in lunar permanently shadowed regions (PSRs) has an existing buyer[1] and requires copious power, which will need to be either generated inside the PSR or transmitted into it. Feasible sources of power inside PSRs include: 1.) A colocated nuclear reactor, 2.) Wired transmission of electricity from a photovoltaic generator in a highly illuminated region, 3.) Reflection of sunlight into the PSR by heliostats located in a highly illuminated region, 4.) Wireless transmission of electricity from a photovoltaic generator in a highly illuminated region (using microwaves), 5.) Wireless transmission of electricity from a photovoltaic generator (using near-visible lasers/optical transmission) [2].

Methods: To perform this trade study, we ascertain preliminary requirements for power supply for a reference propellant manufacturing facility in a lunar PSR. Distances from crater rim to production site are on the order of kilometers and power requirements are 2MW thermal and 0.8MW electric. We explore solar power generation and transmission concepts [3] and compare those to a colocated nuclear reactor baseline. Preliminary power generation and transmission concepts are defined to the extent necessary to illustrate comparative factors. Sensitivity analysis is performed on the defined concepts highlighting environmental and technical risk factors.

Multiple aspects of each trade option are immediately apparent, including the following:

The first trade option, co-located nuclear reactors, contains the advantages of high levels of dependable power at lunar base locations and relatively advanced technological development, with the disadvantage of relative difficulty of scalability and political liability.

The second option, wired transmission, has been explored in detail in [2] (pg. 35). It contains similar problems to the first option with regard to difficulty in mass delivery (or alternatively, in-situ production of transmission lines), while containing the advantage of relative advancement in technological advancement. The laying of transmission wires across lunar terrain also poses challenges.

The third, reflected sunlight, requires slightly more technological development (in order to accurately control the reflection of solar energy to desired locations in the PSRs), and requires addressing of considerations such as reflector aiming, redundancy around the crater rims required to constantly reflect sunlight into the crater (e.g. 3 reflectors at different sites around the rim), and the geometrically imposed limitations of cosine efficiency on reflectors.

The fourth and fifth options, transmission via microwave or laser, offers attractive power density and scalability, while hurdles to development include efficiency, frequency concerns, and rectenna size (i.e. impact on mass delivery requirements); requiring extensive (and likely government-sponsored) development efforts.

Preliminary analysis was performed on each of the above concepts taking into account (among other factors) power conversion efficiency ratios, the state of the art of the technology required, the scalability of the solution, and the ease of either shipping the required equipment to the Moon or manufacturing it in-situ.

Conclusions and Follow-on Work: The results of the analysis highlight the advantages and drawbacks of the power generation and transmission concepts analyzed above, clarify their different potential uses in a power infrastructure, and as such constitute valuable inputs into their respective feasibility, enabling detailed design of power infrastructure for the Moon in the coming years: particularly for scientific, exploration, settlement, and mining bases in the PSR. Moreover, power infrastructure is precisely the area of settlement where government investment and guidance has been most predominant on Earth, and likely will continue to be on the Moon, especially while the state of lunar settlement is in its embryonic stage. Future work will therefore likely not only involve detailed design based on the groundwork laid through this trade study, but factor heavily into major government involvement in settling the Moon.

References:
The potential for maintaining an ongoing Lunar human presence, both in orbit and on the surface, requires the construction, operation and delivery of several critical components in preparation of this objective. In-situ resource utilization (ISRU) has been identified as a critical component and catalyst to promoting the development of this architecture. In early 2018, through signature of Space Policy Directive 1, NASA was directed to refocus its attention to conducting sustainable exploration missions at the Moon. ISRU technology can be designed to process numerous space resources, repurposing them for various uses from rocket propellant and habitat radiation barriers, to launch/landing pads and consumables for astronauts.

Lockheed Martin is the primary contractor for NASA’s Orion crewed vehicle and is one of nine companies to provide payload delivery services to the Moon via NASA’s Commercial Lunar Payload Services (CLPS) contract. With construction of the first Gateway elements planned to start in 2019, along with the upcoming launch of Exploration Mission 1 (EM-1) in 2020, the buildup of NASA’s lunar architecture is already underway. In addition, Lockheed Martin’s design and construction of the Gravity Recovery and Interior Laboratory (GRAIL) has led to several breakthrough discoveries in understanding the Moon in its entirety, through mapping of its gravitational field and interior composition.

Since the 1990s, Lockheed Martin has established a rich background in the design and testing of ISRU technology for use in the solar system. The Precursor ISRU Lunar Oxygen Testbed (PILOT) system, started in 2005, was a built-to-scale ground test article purpose to extracting O2 from lunar regolith at an O2 production rate equivalent to 1000 kg/year. PILOT, working in conjunction with NASA’s ROxygen system (designed to produce O2 at a rate of 660 kg/yr), features a H2 reduction system where it extracts O2 from iron oxides within excavated lunar soil, processing and then storing it for future use. The iron oxides release O2 when chemically reduced by the H2 gas, producing water vapor, which is condensed, filtered, and electrolyzed for later use. This methodology allows for achieving reaction rates similar to fluidized bed reactors, but without requiring any high gas velocities to fluidize the feed material. Following delivery by an excavator, a v-shaped bin is mechanically actuated to raise and lower the excavated lunar soil into the system’s reactor. The system’s tumbling reactor (i.e. a ‘cement mixer’) is designed to mix and heat the regolith at an optimized angle, allowing for maximum exposure of the regolith grains to the hot H2 gas within the conical-shaped reactor without requiring a uniform particle size distribution. The water vapor, a bi-product of the H2 reduction process, is recaptured for use as a filtering media with the PILOT’s purification module, removing contaminants (hydrogen sulfide, chloride, and sulfide) that would inhibit the operation of the system’s electrolyzer. In 2008, while installed on a mock (Phoenix-sized) lander platform, PILOT participated in field tests at the Mauna Kea volcano on the big island of Hawaii. Integrated with the Cratos mini rover equipped to bring regolith simulant (JSC-1A) to the reactor, the PILOT ground test article produced 150 g of O2, equating to total O2 yields of 1 wt% of the processed regolith. Based on 11.6 kg of simulant loaded into the PILOT reactor, ~110 ml of clear, color-free water was produced [1,2,3].

Future human missions to the Moon will rely on a sophisticated, state-of-the-art infrastructure, both in orbit and on the surface. With the spacecraft and services already available for meeting those objectives (e.g. Orion, Gateway, and CLPS), the opportunity to advance ISRU technology is ready to support the early stages of NASA’s lunar architecture buildup. Revitalization of previously proven technology, such as PILOT, will allow NASA to press ahead on those advancements already made with ISRU. Improvements to the PILOT system, based on those lessons learned from its 2008 ground tests (e.g. filter sizing, reactor sealing, etc.), will allow for more significant breakthroughs in O2 production to occur. Additional terrestrial-based testing will allow for the development of a PILOT flight model that can delivered via CLPS, becoming the first major piece to drive NASA’s deep space architecture for sustaining humans at the Moon.

SUSTAINABLE LUNAR IN-SITU RESOURCE UTILISATION = LONG-TERM PLANNING. A. A. Ellery1,
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Introduction: Sustainability will be an essential component of lunar in-situ resource utilization (ISRU) on the Moon if we are not bring all our bad habits with us from Earth, yet few proposals consider sustainability systematically. The spirit of sustainability is to ensure that future generations are not faced with a barren wasteland as a result of desolation by our wanton practices. Implicit in this definition is the need to plan our ISRU practices over the long-term to ensure: (a) we do not consume scarce resources; (b) we employ renewable technologies as far as is feasible; (c) we adopt processes that do not yield toxic material; (d) we minimize waste through recycling loops. To observe this, we need to design a long-term approach to lunar ISRU that adopts the philosophy of indigenous peoples – exploit that which is abundant and waste nothing. As a corollary to this, we cannot simply transport terrestrial technology in toto to the Moon – terrestrial technology is dependent on a global infrastructure that founds it. For example, a smart phone comprises some 50 different materials, not including the processing reagents. We must live off the land as much as possible to minimize our reliance on an Earth-based supply chain. To that end, we have constructed a lunar industrial ecology.

Lunar Demandite: The first step in defining our lunar ecology is to determine our needs. We assume that there is no human presence on the lunar surface though we do not disbar it. Most ISRU proposals are focused on the supply of consumables such as water, oxygen and liquid hydrogen/oxygen propellant/oxidizer. We discount this for 4 reasons (though oxygen is a byproduct of our lunar ecology): (i) current environment control and life support systems (ECLSS) are highly efficient in recovering and recycling oxygen and water so only leakage resupply rather than primary resupply is necessary; (ii) liquid hydrogen/oxygen require long-term cryogenic storage (liquid hydrogen requires temperatures below 20 K) which will be challenging; (iii) hydrogen is a scarce resource except in difficult-to-access permanently-shaded craters at the poles; (iv) propellant/oxidizer consumption can be replaced with abundant and renewable solar-electric power for rover surface sorties and electromagnetic launchers for transport to lunar orbit.

Rather than focusing on building specific products from lunar material, we have adopted to build the means of production. In essence, we are attempting to build a universal construction mechanism from lunar resources which will enable us to build a wide suite of products. Specifically, we wish exploit lunar resources to build mining machines, unit chemical processors, manufacturing machines and assembly machines. The common factor is that they are all robotic machines. This is corroborated by John von Neumann’s universal constructor concept which comprised of a computer controlling an abstract robotic machine. Any kinematic machine may be characterized as a specific configuration of actuators. Hence, we have selected two key components to be manufactured from lunar material – electric motors for robotic actuation and vacuum tubes (rather than solid-state manufacturing) as the key component in computing machines (in this case, based on analogue neural network architectures rather than CPU-based architectures). They also provide the basis for electrical energy generation (thermionic conversion of Fresnel lens-based thermal energy) and storage (motorized flywheels).

Lunar Ecology: We have built a lunar ecology that processes lunar minerals and volatiles into materials to construct our electric motors and vacuum tubes. We require NaCl imported from Earth as a recycled reagent (it is not consumed). We also assume that meteoritic material is available from which a variety of alloying metals can be extracted via the Mond process. Volatiles of interest include hydrogen (from water), carbon compounds and small amounts of nitrogen which can be extracted thermally and fractionally condensed. The carbon provides the basis for silicone plastic manufacture. The lunar minerals that we process to extract metals include ilmenite (Fe and Ti), anorthite (Al), orthoclase and pyroxene. With mineral preprocessing, the Metalysis FFC process can reduce metal oxides into pure metal as a solid-state sintered cathode suitable for 3D printing processes. Its CaCl2 electrolyte is manufactured as a byproduct of metal extraction.

3D Printing: We have adopted 3D printing as our universal manufacturing technique. We have demonstrated 3D printing of an electric motor except its wire coils but the latter is in process. We have 3D printed testpieces of almost all the materials required to construct a vacuum tube (specifically, a magnetron). We are constructing a custom 3D printer to print metal and silicone plastic simultaneously. Once complete, we shall then proceed to lunar analogue material.

Conclusion: We are in the process of demonstrating that key components to a lunar industrial ecology can be constructed from lunar-like material. The lunar ecology is essential if ISRU is to be sustainable.
OPERATIONS MODELING OF ISRU LUNAR BASE ARCHITECTURES. J. O. Elliott¹, A. Austin¹, and B. Sherwood¹, ¹Jet Propulsion Laboratory, California Institute of Technology (4800 Oak Grove Dr., Pasadena, CA 91109, jelliott@jpl.nasa.gov)

Introduction: The moon is rapidly returning to prominence as a near-term destination for robotic and human exploration. The framework for the development of architectural elements outlined by NASA and the rapid progress being made by the commercial sector are combining to form the seeds of a sustainable architecture that may allow global exploration in a manner not previously achievable. A central theme is the establishment of a lunar “base”, i.e., a hub for surface activities, including production of consumable volatiles for transportation and life support.

Our team is investigating robotically constructed base architectures to support human and robotic exploration. Our analysis method starts with defining an operational base, then “works backwards” to understand requirements and concepts of operation at each stage of construction. A driving base requirement is production of useful quantities of water-based volatiles (liquid oxygen and hydrogen), primarily for propellant for a surface-based, reusable lander.

Our operations model takes as input fundamental parameters, including regolith ice content, energy per ton for excavation, transportation, etc., and a range of technologies and infrastructure elements; then sizes the systems to meet operational requirements. By FY20 the model will accommodate a wide range of base scenarios, allowing comparative assessment of exploration concepts.

New Findings: To develop the model, we defined distinct base scenarios. One locates the base including ISRU production facilities entirely in a permanently shadowed region (PSR). Here ice content in the regolith is predicted to be relatively high (of order 5 wt%), imposing challenging excavation and processing geotechnical properties and complications for physical access, cold operations, and provision of power and telecomm. A second locates the base in a “persistently illuminated” region, simplifying power and telecomm, but relying on regolith with lower ice fraction (≤ 2 wt%).

By exercising the model on these two scenarios, we demonstrate how integrated operations-based analysis of base architectures yields surprising findings not accessible to suboptimized analysis methods.
SUPPORTING ISRU MISSIONS THROUGH MISSION CONTROL SOFTWARE. M. Battler¹, M. Faragalli¹, E. Reid¹, M. Cole¹, K. Raimalwala¹, E. Small¹, M. Vandermeulen¹, and M. Aziz¹, ¹Mission Control Space Services Inc. (1125 Colonel By Drive, 311 St. Patrick’s Building, Ottawa ON K1S 5B6, Canada. melisa@missioncontrolsparseervices.com, michele@missioncontrolsparseervices.com).

Introduction: In the coming years there will be a paradigm shift in space exploration from government to commercial missions, which will include commercial in-situ resource utilization (ISRU) missions. Private companies will launch, land and deliver payloads to the lunar surface primarily for anchor government customers through programs such as NASA’s Commercial Lunar Payload Services (CLPS), Lunar Surface Instrument and Technology Payloads (LSITP) and ESA’s Lunar Exploration Campaign Science and Payload.

While early commercial flights will see small, single-use tele-operated rovers with limited autonomy used to deliver payloads and provide data to Principal Investigators (PIs), the resulting 2-week missions will be time- and operator-intensive and, ultimately, expensive to operate.

Although these rovers will be able to accomplish basic technical objectives, more autonomous behavior – such as terrain perception, path planning, control or data analytics – would reduce operator workload, enable more distributed ground operations, enable multi-rover collaborative prospecting missions, and increase the safety, yield and efficiency of ISRU rover or lander mission(s) [1,2,3,4]. Further, private companies will have economic incentives not only to make missions more efficient and productive, but to reuse software across multiple payloads and missions.

We foresee a growing and near-term demand for an easily accessible, on-demand mission control software that would provide geographically distributed operations for commercial space companies, mission and payload operators, and researchers.

Mission Control Software (MCS): Mission Control Space Services Inc. (Mission Control) is developing the Mission Control Software (MCS) to address emerging operations and autonomy needs in upcoming privately-led lunar ISRU (and other) missions. MCS is a cloud-based solution that enables operation of lunar spacecraft (e.g. payloads, rovers), while securely distributing data access and command responsibilities to any number of users involved in a mission. MCS would also allow operators to offboard certain guidance, navigation and control algorithms to the ground segment, enabling more autonomous behavior for computationally limited platforms [5], such as microrovers – where direct teleoperation is widely considered a baseline concept of operations [6].

Through this technology, Mission Control brings the Software-as-a-Service (SaaS) paradigm to space exploration and extends it by offering Mission-as-a-Service and Data-as-a-Service layers to the emerging market of service-based commercial lunar missions.

How MCS Supports ISRU Missions: MCS would have direct applications to ISRU characterization, prospecting, and extraction missions, which would make use of instruments to measure and verify the extent of potential resource deposits, determine the composition of/orm these resources are in, and conduct resource extraction. Landed missions of this nature would likely involve rovers in different locations, which would in some cases need to converge on/travel to areas of maximum resource concentration. MCS would directly benefit these missions by providing improved guidance, navigation, and control capabilities, storage of pertinent data collected by science instruments and transmission to ground operators and science teams, and allow for data sharing across multiple rovers or landers, which could facilitate greater autonomous capability.

Examples of algorithms that will be deployed in MCS include the Autonomous Soil Assessment System (ASAS) that uses data in real-time to learn terramechanics models for non-geometric hazard prediction; the Skid Steer Optimizer (SSO) that can plan energy-optimizing maneuvers for skid steer vehicles; and the Intelligent Planner that uses predictive capabilities by ASAS and SSO to plan multi-objective path profiles that minimize hazards and energy consumption.

Commercial Involvement in ISRU Missions: In addition to directly benefiting ISRU missions, MCS is an example of commercial involvement in ISRU missions, and highlights one area of commercial interest around ISRU. This is an example of a commercial product/industry that can grow out of ISRU, and also support NASA’s plans for Gateway and human lunar landings in the latter half of the 2020s. Data storage/transmission and communication aspects of MCS could be just as relevant to human missions as robotic missions.

Construction of Infrastructure is the Key to Establishing a Cislunar Economy. Nathan Gelino¹, Brad Buckles², Rob Mueller³, ¹National Aeronautics and Space Administration (NASA), Kennedy Space Center (KSC), Granular Mechanics and Regolith Operations (GMRO) Laboratory, NE-L6, FL 32899, nathan.j.gelino@nasa.gov. ²Bionetics, NASA, KSC, GMRO, Building M7-409, Room: 1024, FL 32899, bradley.buckles@nasa.gov. ³NASA, KSC, GMRO, UB-R1, FL 32899, rob.mueller@nasa.gov.

Introduction: Infrastructure has proven to be the backbone of strong Earth based economies because it enhances private industry’s ability to produce and exchange goods and services. The provision of Government funded infrastructure in Cislunar space and on the lunar surface will be pivotal in establishing and anchoring a vibrant Cislunar economy. The lunar surface has the potential to support the market by providing valuable raw materials and supplying locations for the production and exchange of goods and services. Lunar surface infrastructure is necessary to exploit the resources. Examples of such infrastructure include: launch/landing pads, plume deflectors, habitats, cryogenic dewars, storage facilities, radiation shelters, power, transportation systems, life support systems and many others. Numerous ISRU materials and construction technologies have undergone preliminary development and show promise for lunar surface operations. Government, industry and academia must work together to define the highest return on investment areas for government funded infrastructure The construction technologies supporting these areas should be funded and developed to operational readiness to support the Cislunar economy.

http://thespaceeconomy.blogspot.com/2014/05/the-moon-is-best-start.html
NUCLEAR POWER DEMONSTRATION IN A PERMANENTLY SHADOWED REGION OF THE MOON  S. T. Goertzen¹, A. B. Conners², R. Gregg³, A. Hugo⁴, N. Webb⁵ and H. Williams⁶

Introduction: The goal of this project is to develop a power demonstration system for use in a permanently shadowed region on the lunar surface. By using the current advancements in nuclear fission reactors along with the long history of nuclear power used by previous missions in space, this project will demonstrate power production for in situ resource utilization where sunlight is not readily available. Nuclear power offers the benefit of nearly constant power output and availability without needing a relay system from the edge of a crater like many other power systems rely on.

Technical Systems: Our preliminary design is made up of components currently being developed for use in space and features a scaled Kilopower nuclear fission reactor capable of producing electrical power and thermal energy. Another benefit of nuclear fission reactors is that as they are increase in power, their power to mass ratio increases making larger reactors more efficient. Launching within a single payload, the system will interface with a modified commercially available lunar lander. Working alongside the reactor is a thermal radiator system which will autonomously keep the internal temperatures within the operation range and transfer any excess heat either into an ice sublimation system or into the vacuum of space. A data and telemetry system will monitor all internal systems as well as any external instruments and transmit the data back to earth via a lunar satellite relay. In addition to the ability to power external instruments, there will be an external power adapter for rovers to recharge or for external systems to connect.

Feasibility: Using a development cost and launch cost per kilogram model along with a maximum budget of 200 million US dollars, the overall mass limit is calculated to be 2300 kilograms excluding the mass of the commercial lander. By achieving this requirement, the project will be financially and physically feasible to achieve.

Potential Applications: This system enables greater production of water on the lunar surface by using the excess heat for ice sublimation while simultaneously providing electrical power and reducing the amount of wasted energy. Along with enabling resource extraction on the lunar surface, this also system enables potential applications all across the solar system by taking away the necessity of using the sun as an energy source. Since solar flux varies by one over the distance from the sun squared, the solar power generated decreases quickly one travels farther away from the sun. Even at only 1.5 astronomical units (roughly the distance from the sun to Mars), the solar flux has already decreased by more than 50 percent.

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Introduction: Most recent discussions about the utilization of lunar resources have focused on water ice at the lunar poles [1]. While the potential value of polar water ice, and other frozen volatiles, may be huge, the scientific data for these potential resources is not yet sufficient to conduct a viable resource assessment. Surface water frost has been measured by several instruments from orbit, yet the datasets are not in agreement in many surface locations [2]. Also, neutron spectrometer data of the shallow subsurface does not correlate well with the surface data [3]. Surface-based mapping by mobile surveyors and prospectors will be needed to better define the distribution of polar water ice.

The unknown quantity of polar volatile deposits is matched by the unknown accessibility of these deposits. Permanent darkness in crater floors and steep slopes to reach those floors, temperatures below 40K, and intermittent direct communications with Earth will frustrate initial attempts to mine the polar volatiles [4, 5].

While the existence of the polar volatiles deposits is scientifically intriguing, the polar regions are not high priority locations for other important outstanding lunar science questions [6]. An exception to this is the idea that Malapert peak and the Leibnitz B plateau may be remnants of the South Pole-Aitken basin rim, and the ridge that is bounded by Shackleton and De Gerlache craters may be a SPA inner ring segment [7]. Both areas could provide important data on the age and formation of the SPA basin.

An alternative location for a near-term lunar outpost and in situ resource utilization (ISRU) strategy is the northwest quadrant of the lunar near side. Known resource deposits, numerous important scientific locations, and continuous line of sight communications with Earth make this region a useful and viable initial proving ground for long-term exploration, utilization, and habitation of the Moon.

A Vast Resource Potential: Orbital remote sensing datasets have shown the vast flood basalts on the northwest nearside possess some of the highest titanium contents of the mare basalts on the Moon [8]. Furthermore, the boundaries of the regional pyroclastic deposit on the Aristarchus Plateau are well delineated by spectral reflectance [9]. Recently, this pyroclastic deposit has been shown to have a higher amount of hydration than surrounding areas [10]. Both the high-Ti basalts, and the Aristarchus regional pyroclastic deposit are ideal feedstocks for the hydrogen reduction process to produce oxygen [11]. The hydrogen reduction process is the relatively most simple process to liberate oxygen from the lunar regolith.

Abounding Scientific Enigmas: The northwest nearside of the Moon abounds with scientifically interesting and important locations. The Gruithuisen domes, Aristarchus Plateau and the young lava flows south and west of plateau, the Marius Hills volcanic complex and a skylight into a possible intact lava tube, and the magnetic anomaly Reiner Gamma, are all described as high-priority landing sites in the recent Lunar Science for Landed Missions Workshop Findings Report [12]. All of these locations are within reach of robotic or human pressurized rovers, based from a centrally-situated outpost.

Challenges: While the northwest quadrant of the lunar nearside is replete with potential resources and scientific investigations, it does come with its own set of challenges. The primary challenge is associated with the diurnal cycle on the surface of the lunar near side, namely an extreme temperature range of 100s °C, and the two-week long lunar night.

Prospective Study for Harvesting Solar Wind Particles via Lunar Regolith Capture. H. L. Hanks

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Introduction: In the 1970s, experiments on Apollo lunar regolith samples demonstrated the existence of volatiles which could be released upon heating to approximately 700 °C.1

In 2009 data from lunar orbit-based detectors Chandrayaan-1 and LRO confirmed the existence of OH on the surface of the Moon2 and even showed OH migration from equatorial regions to cold traps3.

It is believed that water continues to accumulate on the Moon via comet impacts4 and solar wind implantation of protons,5 but questions remain about how much of it diffuses into the subsurface, escapes into space or hops into cold traps.

What is known is that some proportion of the solar wind ions have reacted with oxygen in the regolith over millennia to form around 150 ppm H2O, CO, CO2, and N2 which can be extracted upon heating6. There is also evidence that these volatiles can be found at least 3m down, at the bottom of Apollo’s core sample drills6.

Non-PSR Regolith Mining: Much of the current Lunar ISRU research focusses on mining perennially shadowed regions (PSRs) where larger concentrations of water ice are believed to exist. However, there are some reasons to consider mining non-PSRs:

1) Only about 1% of the lunar surface consists of PSRs7.
2) Mining operations can be executed during daylight hours with illumination and abundant solar energy.
3) Temperatures in the PSRs can be just a few degrees above absolute zero8, so the risk to personnel and equipment is significant.
4) Mining in non-PSRs can be carried out on flat surfaces with well-mapped terrain. This provides more safety and operational certainty for volatiles mining activities.
5) Mining sites can be chosen to align with other mission objectives such as building settlements and landing and launching of spacecraft.

Process Engineering Approach: Previous studies of volatile extraction from lunar regolith noted that a useful gas pressure can be achieved but the expected heating requirements are daunting9. However, heat integration was not considered in the calculations.

The aim of the current research is to use standard process engineering techniques combined with available lunar environment information to design a Solar Wind Activated Material Processor (SWAMP) module.

The design is considering a range of possible technologies to achieve the following process steps:

1) Regolith extraction and loading
2) Heating and pyrolysis of the regolith
3) Cooling and heat recovery
4) Separation of volatile products
5) Purification and compression
6) Process integration to maximise heat recovery

As part of the process engineering project, legal, environmental, reliability, safety and infrastructure concerns will be considered in the prospective study.

References:
9. Rapp, D. Use of extraterrestrial resources for human space missions to moon or mars. Use of Extraterrestrial Resources for Human Space Missions to Moon or Mars (Springer Berlin Heidelberg, 2013). doi:10.1007/978-3-642-32762-9
INTEGRATING ISRU PROJECTS TO CREATE A SUSTAINABLE IN-SPACE ECONOMY. G. Harmer¹, ¹Space Centric, LLC, 5703 4th Ave #1512, Ferndale, WA 98248 (gord@space-centric.com).

Introduction: This abstract is for a poster showing how integrating all the various lunar ISRU projects can have a big impact on how much (if at all) they contribute to the formation of a sustainable in-space economy.

The poster will show:

Definitions. We can’t create something unless we agree on what it is we’re trying to create.

What this integration could look like. Combining diverse lunar ISRU research projects into an interdependent ecosystem of economic activity provides opportunity for growth and supports commercial interest and involvement.

Cohesion with Congress and the public (voters).

How it provides economic justification for human presence.
ADDITIVE MANUFACTURING OF LUNAR MINERAL-BASED COMPOSITES. A. K. Hayes, P. Ye, D.A. Loy, K. Muralidharan, B.G. Potter, and J.J. Barnes. 1Department of Materials Science & Engineering, The University of Arizona, 2Department of Chemistry & Biochemistry, The University of Arizona, 3Department of Materials Science & Engineering, The University of Arizona, 4Department of Materials Science & Engineering, The University of Arizona, 5Department of Materials Science & Engineering, The University of Arizona, 6Lunar & Planetary Laboratory, The University of Arizona.

Introduction: One major challenge in establishing a lunar base is the ability to enable manufacturing without carrying large amounts of material from Earth [1]. Additive manufacturing is an attractive option for rapidly producing parts on-demand and with little waste. By using portable equipment, avoiding toxic solvents, and maximizing the use of in situ resources, additive manufacturing methods can be readily adapted for the manufacturing of complex parts at a lunar base. This work examines the use of abundant lunar mineral resources for inexpensive, low-energy additive manufacturing that requires minimal processing to create feedstock.

Methods: JSC-1A and LMS-1 lunar regolith simulants were examined as the material base for printing structural and device components [2]. Regolith simulants were processed to create suitable additive manufacturing feedstock. In conjunction with acrylonitrile-butadiene-styrene (ABS), composites containing up to 5 wt.% lunar regolith simulant were used in fused deposition modeling (FDM) to create structural components. A low viscosity thermally reversible thermoset was explored to create elastomeric structures containing more than 30 wt.% lunar regolith simulants.

Conclusions: Portable, bench-top equipment was used for additive manufacturing utilizing in situ resources. Filaments with powder loading up to 30 wt.% were achieved and used in a commercial FDM printer to fabricate structural artifacts, while higher loading was achieved in printing similar structures using commercial robocasting equipment. This work paves the way for direct in situ resource utilization for manufacturing of structures and devices on the Moon.

LANDING SITE SELECTION AND EFFECTS ON ROBOTIC RESOURCE PROSPECTING MISSION OPERATIONS. J. L. Heldmann¹, A. C. Colaprete¹, R. C. Elphic¹, and D. R. Andrews¹. ¹NASA Ames Research Center, Moffett Field, CA 94035.

Introduction: The Moon’s polar deposits are considered high priority targets for lunar in situ resource utilization (ISRU) [1]. These resource deposits can enable long term human exploration and settlement of the Moon. Characterization of these resource deposits is critical to verify the form and distribution of volatiles in order to inform future ISRU architectures. Here we discuss optimal robotic mission strategies for resource assessment and verification, and emphasize the importance of site selection and its implications for resource prospecting and ISRU operations.

Robotic Resource Prospecting: Remote sensing data coupled with theoretical modeling has suggested the presence of significant volatile deposits in the lunar polar regions. Verification and characterization of these potential resources is required on the scales of ISRU operations. Such information is required to determine key parameters such as 1) volatile distribution including concentration, lateral and vertical extent and variability, 2) overburden quantities to determine how much material requires excavation to reach the ore, and 3) the working environment including factors such as the fraction of time in sun/shadow, soil mechanics, trafficability, temperatures, etc. [2]. This information is needed to determine if the resource and processing technique present an acceptable risk profile and expected economic return on investment. The in situ measurements are also needed to ground truth models and remote sensing datasets in order to develop robust predictive capabilities for other resource deposits.

The optimal method for robustly obtaining this data is through in situ measurement with a mobile robotic asset(s) [3]. A lunar polar rover mission can characterize the distribution of water and other volatiles at the scales necessary for ISRU. Candidate prospecting instrumentation for such a mission includes a drill for subsurface access and a Neutron Spectrometer System (NSS) and Near InfraRed Volatiles Spectrometer System (NIRVSS). NSS is capable of detecting a water-equivalent hydrogen 40.5 wt% down to about 1 m depth, and thus is sensitive to volumetric hydrogen [4, 5]. NIRVSS is used for identification of surface H2O/OH and other volatiles and near-subsurface sample characterization [5, 6].

Site Selection: Site selection is a key driver of the lunar polar rover prospecting mission duration and hence of the mission concept of operations. Recent work has shown that stable ice may exist outside of permanently shadowed regions (PSRs) near the lunar poles. Thermal modeling coupled with Diviner lunar radiometer measurements from the Lunar Reconnaissance Orbiter (LRO) has shown that cryogenic temperatures exist outside of PSRs in near-surface regions [7]. Figure 1 shows a map of depth to stable ice for the lunar south polar region. Areas where the depth to stable ice is zero meters (white regions in Fig. 1) are primarily regions of permanent shadow. All other regions with a range of depths greater than zero and up to one meter are areas that receive on the order of several days of sunlight per month. The low sun angle coupled with the relative short duration of solar illumination results in the cryogenic subsurface temperatures which enable cold-trapping of water ice and other volatiles, even outside of permanently shadowed regions.

Implications for Operations: Lunar polar ISRU activities are not restricted to PSRs. ISRU prospecting and operations can be conducted in sunlight which enhances visual situational awareness during mission operations, subjects hardware to more favorable thermal regimes compared with PSRs, and provides the option of solar power. Also, human settlements on the Moon will not be located in PSRs, thus a resource feedstock outside of a PSR would allow for closer proximity to the human base and avoid the engineering challenges of long-term PSR operations for ISRU.

References:
Secular mapping of water on the Moon from a Near-Rectilinear Halo Orbit. C. A. Hibbitts, Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Rd., Laurel, Md. 20723. Karl.hibbitts@jhuapl.edu

Introduction: Near rectilinear halo orbits (NRHO) about the Moon [1,2] offer potential long-term low energy orbits for spacecraft in the cis-lunar region that have relatively low resource transfer options from the Earth as well as to the surface of the Moon. This type of orbit is being considered for the Lunar Deep Space Gateway and could also be accessed by low cost spacecraft. These Earth-Moon NRHOs have perilune radii as low as a few hundred km and apolunes 10000’s km, with periods ranging from about 6 to just over 10 days. These stable, easy to access, long period and distant orbits are ideally suited for extended observational campaigns of the Moon.

Mission Concept: One such concept is a variant of the Lunar WATER mission concept [3], whose goal is to understand the nature, origin, and evolution of the water on the surface of the Moon [4,5,6]. There remain fundamental questions, including: (1) how much of this water is hydroxyl (OH) and how much is molecular (H2O); [2] does abundance vary with time and or temperature; (3) is there a ‘water-cycle’ of production on the illuminated Moon, loss, and then accumulation on colder portions of the Moon?; (4) is this water a potential resource to support future exploration of the surface? Infrared spectral mapping in the 3 to 6 micron range, at the long distance as well as high resolution and over the long periods afforded by NRHO orbits can address and possibly answer these questions. The NRHO has some advantages over lower altitude high spatial resolution mission concepts. One advantage an NRHO offers is the ability to “see globally”. Processes affecting the water on the surface of the Moon are likely varied and intertwined, so that imaging all or most of the Moon at a single instance can enable disentanglement of thermal, photometric, and large scale compositional effects on water abundance and composition. The long duration possible for a NRHO mission can uncover trends and discern secular variations on times scales of a lunations, lunar seasons, and variation in solar influences (such as occurs during passages through the Earth’s magnetotail).

Introduction: Lockheed Martin has designed a lunar lander to carry a variety of small to medium-class payloads to the surface of the Moon. The lander, named for astronaut Bruce McCandless, was selected by NASA as a candidate in the Commercial Lunar Payload Services catalog in late 2018 [Ref 1]. McCandless Lunar Lander capabilities are particularly relevant for ISRU pilot plants or resource exploration rovers, which require more power and mass than many other types of lunar payloads.

Experience: The design, flight software, and operations concept of the McCandless Lunar Lander (Fig. 1) is based on Lockheed Martin’s history of developing, building, and operating numerous planetary spacecraft in partnership with NASA and JPL, from Viking to OSIRIS-REx. It particularly draws on aspects of the Phoenix and InSight Mars landers, and the GRAIL A & B lunar orbiters. Like McCandless, these missions involved integrating multiple payloads with differing requirements. LM planetary missions have a strong track record of meeting unforgiving planetary launch schedules.

Payload Accommodations: In addition to accommodating collections of distributed smaller payloads, the McCandless Lunar Lander is designed with the capability to carry large, monolithic payloads such as a rover or ISRU pilot plant (Fig. 2). The large, flat payload deck, with approximately 5 m² of payload area, is positioned only 1 m above the lunar surface to simplify egress of a rover or access for a sample collection arm. Smaller payload volumes are available suspended underneath the top deck for payloads which need to be closer to the lunar surface or need a more isolated thermal environment inside the lander thermal blankets.

The lander can deliver in excess of 250 kg of payload mass to most locations on the lunar surface and is adaptable to larger payload masses if required.

A large solar array provides 400 W of payload power at ~28 VDC during lunar surface operations. In order to maximize the useful mission duration, the array is mounted on a Sun-tracking gimbal, enabling landing shortly after lunar dawn and full-power operations throughout one lunar day, for a total landed mission duration of about 315 hrs depending on latitude and local terrain at the selected landing site. The lander is presently designed only to operate for one lunar day, but upgrades for surviving the lunar night can be considered depending on mission requirements. A portion of the top deck is reserved for radiator area, depending on the landing site latitude and payload power duty cycle.

Conclusions: The McCandless Lunar Lander is capable of carrying substantial payload mass to the lunar surface. It can accommodate a prospecting rover or ISRU pilot plant and provides the power levels required to run high-power payloads such as ISRU processing experiments.

References:


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The Use of Lunar Resources for the Construction and Operation of a Lunar Radio Observatory on the Moon
Alex Ignatiev, Peter Curreri, Donald Sadoway, and Elliot Carol, Lunar Resources (alex@lunarresources.space, elliot@lunarresources.space)

Introduction: The indigenous resources of the Moon can be used to develop a Radio Astrophysical Observatory on the far side of the Moon. Based on available lunar resources a Radio Observatory located on the far side of the moon can be founded on the fabrication of a strip wire antenna or a dipole antenna array by thin film growth technology in the vacuum environment of the Moon. This can be accomplished by the deployment of a moderately-sized (~200kg) crawler/rover on the surface of the Moon with the capabilities of preparation of the lunar regolith for use as a substrate, evaporation of the conductive metals to fabricate dipole antenna arrays directly on the regolith surface of the Moon, or deposit strip wire antennas inside a lunar crater to simulate a parabolic focusing antenna. Further, a power generation and transmission system can be fabricated by the same crawler/rover to supply the antenna system with the required energy for operation. The raw materials for the lunar fabrication process would be extracted from the lunar regolith by molten oxide electrolysis and supplied to the crawler/rover for deposition. The direct fabrication of a Lunar Radio Observatory on the Moon would result in the transportation of a much smaller mass of equipment to the Moon than would otherwise be required for the transport and installation of a terrestrially fabricated microwave antenna system including a power system. The fabrication of a microwave antenna system on the Moon from lunar resources would also result in a radio observatory architecture that was repairable/replaceable through the simple fabrication of more additional dipole antennas or wire, and that would yield various spin-off applications to foster an cis-lunar economy.

References:
The Use of a Lunar Vacuum Deposition Paver/Rover to Eliminate Hazardous Dust Plumes on the Lunar Surface
Alex Ignatiev and Elliot Carol, Lunar Resources, Inc., Houston, TX (alex@lunarresources.space, elliot@lunarresources.space)

Introduction: The indigenous resources of the Moon and its natural vacuum can be used to prepare and construct various assets for future Outposts and Bases on the Moon. Based on available lunar resources and the Moon's ultra-strong vacuum, a vacuum deposition paver/rover can be used to melt regolith into glass to eliminate dust plumes during landing operations and surface activities on the Moon. This can be accomplished by the deployment of a moderately-sized (~200kg) crawler/rover on the surface of the Moon with the capabilities of preparing and then melting of the lunar regolith into a glass on the Lunar surface. The direct fabrication of Lunar regolith glass on the Moon would require the transportation of a much smaller mass of equipment to the Moon than would otherwise be required to eliminate hazardous dust plumes on the Lunar surface due to surface operations. The crawler/rover coupled with a regolith electrochemical processor yielding raw materials could also be used to develop the Lunar infrastructure including: a PV power system (solar cells and transmission wire), a Lunar radio observatory and fabricate a variety of functional thin film materials. In addition, such a crawler/rover could have direct applications related to eliminating hazardous dust plumes on the Martian surface due to surface operations.

References:
The Use of Lunar Resources for Energy Generation on the Moon  Alex Ignatiev, Peter Curreri, Donald Sadoway, and Elliot Carol, Lunar Resources, Inc., Houston, TX (alex@lunarresources.space, peter@lunarresources.space, dsadow@lunarresources.space, elliot@lunarresources.space)

Introduction: The indigenous resources of the Moon can be used to develop an electrical energy system for the Moon. Based on available lunar resources a lunar power system can be generated founded on the fabrication of silicon solar cells by thin film growth technology in the vacuum environment of the Moon. This can be accomplished by the deployment of a moderately-sized (~200kg) crawler/rover on the surface of the Moon with the capabilities of preparation of the lunar regolith for use as a substrate, evaporation of the appropriate semiconductor materials for the solar cell structure directly on the regolith substrate, and deposition of metallic contacts and interconnects to finish off a complete solar cell array. Raw materials for the crawler/rover will be supplied by processing the lunar regolith for extraction of silicon, aluminum and other materials of importance to the manufacturing process. The raw materials extraction will be by molten oxide electrolysis which would be staged to attain the materials quality needed for solar cell fabrication. The direct fabrication of an electric power system on the Moon would require the transportation of a much smaller mass of equipment to the Moon than would otherwise be required to install a complete electric power system brought to the Moon from the Earth and emplaced there. It would also result in an electric power system that was repairable/replaceable through the simple fabrication of more solar cells, and that would yield an energy-rich environment for the Moon and cis-lunar space.

References:
Introduction: The potential of utilizing lunar regolith as the raw material for manufacturing structural members is very appealing for future exploration of the Moon [1,2]. Future lunar missions will depend on in-situ resource utilization (ISRU) for structural components. Manufacturing structural components directly from unrefined lunar regolith would have the advantage of needing less specialized material processing equipment in comparison with refining the lunar regolith for its raw elements. Sintering lunar regolith has been proposed as a structural material by previous researchers but has not been evaluated for its elastic material properties. Sintering can be a highly variable process and only with the material constants can a structure be designed from this material.

Background: Sintering of actual lunar regolith has been accomplished by Taylor and Meek [3] using microwaves. However, there is not enough lunar regolith available for destructive testing to accurately quantify the mechanical material properties of sintered regolith. Lunar simulant substituted for lunar regolith in experiments then becomes the commonplace. The lunar simulant JSC-1A has become the standard for researchers in the topic of structural ISRU. Through a geothermic reaction produced by the inclusion of additives, JSC-1A has been used to fabricate bricks for constructing a voissor dome as performed by Faierson et al. [4]. In addition, Balla et. al. [5] has utilized JSC-1A, filtered for particle size, as the base material in a selective laser sintering (SLS) machine to prove the simulants additive manufacturing potential. As a proof of concept, fabrication of small solid cylinders was performed and the parameters for the SLS machine were evaluated. Focusing on developing an optimal method of sintering lunar simulant, Allen, et al. [6] compared the fabrication of bricks with two unrefined simulants, JSC-1and MLS-1.

Test Results and Data Analysis: Two batches of sintered lunar regolith simulant, JSC-1A samples with porosities 1.44% and 11.78% underwent compression testing. Analysis of the data sets were evaluated based on the comparative material density. Compressive strength compared to the shows two clear classes of material quality. The average compressive strengths of the 1.44% porosity material were 219 MPa, and 85 MPa for the 11.78% porosity material. Material properties were evaluated from the load vs. deflection data acquired. Stress, strain, modulus of elasticity, toughness, the compression strength, bulk modulus. By comparing these values with other ISRU derived structural materials, sintered lunar regolith is expected to be one of the strongest material derived from lunar sources.

A Lunar Power Lander concept is presented that will utilize concentrated solar thermal radiation as an energy source for generating and storing electrical power during the day. The stored power will be available for use during the long lunar nights when there is a lack of solar insolation for power and heating. The proposed lander uses a solid state Johnson Thermo-Electrochemical Converter (JTEC) to convert solar heat directly into electricity. A low mass deployable solar reflector is used to concentrate solar energy onto the JTEC. The projected performance for the converter is in the range of 2kW/kg, excluding support structure, radiator, concentrator and heat transfer components. The concept includes a novel, extremely high specific energy 1.5kW/kg lithium fuel cell for electrical energy storage. The high specific energy of the storage system makes it ideal for space deployments.

In addition, the proposed system provides basic enabling technology for addressing future goals of oxygen generation and mineral extraction from celestial body surfaces, particularly titanium. The high energy storage capability of this low mass system will enable survival of the extreme (>120°C to <-150°C) surface temperature transitions during the 28-day/-night cycle. This high performance storage capability will also be important for use in permanently shadowed regions.
THE USE OF PROSTHETIC ACCELEROMETERS FOR RESTORATION OF NORMAL LIMB MOVEMENTS UNDER MICROGRAVITY CONDITIONS. P. A. Johnson¹,², R. Witiw² and A. A. Mardon², ¹Department of Medical Sciences, University of Alberta (email: paj1@ualberta.ca) ²Antarctic Institute of Canada (103, 11919-82 Str. NW, Edmonton, Alberta CANADA T5B 2W4; email: aamardon@yahoo.ca)

Introduction: Manual dexterity, compensatory mechanisms and controlled movements are all essential for all motor-related tasks and effected in space. In particular, the microgravity conditions in orbit and the lunar surface can be physiologically compromising for humans accustomed to 1-G environments on Earth. Of these, motor and fine-dexterity tasks involving the extremities, particularly in locomotion, grasp and release, are influenced becoming delayed and placing greater force demands. With the accelerating pace of prosthesis developments, research has reached frontiers in the development of biomechanical systems providing both sensory and motor feedback platforms to the user. A recent study has suggested the use of accelerometers in the control of prosthetic arms. The authors hereby propose incorporating this same technological innovation into loading suits designed for use in orbit or celestial environment.

Prosthetic accelerometer model: Conventionally, accelerometers have been designed to utilize input of electromyography (EMG) signals to quantify the neuromuscular signaling patterns of the innervating motor units. Kyberd and Poulton (2017) have previously suggested the use of a tri-axial system whereby sensors and controllers are employed to detect and correct for key motor control elements consisting of 1) segment orientation, 2) motion compensation, and 3) inertial platform. Segment orientation is a compensatory mechanism for the accelerometer that takes into consideration the gravitational forces and tri-dimensional, spatial alignments in order to accommodate the motor demand accordingly. Alternatively, motion compensation adapts for the positioning using the surrounding prosthetic limb segment kinematics. In addition, the inertial platform controller uses holistic, mathematical analysis of prosthesis in interaction with an object of interest.

Loading suit incorporating prosthetic accelerometers: Here the authors suggest the adoption of this accelerometer design within prosthetic elements within loading suits, which use EMGs for input signal detection, quantification, and predictive output modeling. This will be used as a means to effectively reproduce the same tri-axial system utilized by the prosthetic accelerometer model. One of the strengths of this design is that gravitation is not expected to have an effect, as this system exploits the Equivalence Principle, which states that forces due to gravity and acceleration are indistinct. In other words, the gravitational acceleration or otherwise lack of gravity would not affect this feedback system.

This additionally suggests technology can feasibly be designed to accommodate prosthetic and non-prosthetic users in space. This design offers an inclusive design for prosthetic users. Furthermore, for non-prosthetic users, it may be possible to use surface EMGs which use fully non-invasive dry surface electrodes, as opposed to needle electrodes or fine-wire electrodes. As EMGs are the sole input in this model, complex multi-input variable modeling, which are quite common in biosensor feedback systems, can be avoided. It is anticipated that this technology can enhance tasks such as repairs or construction or perhaps in recreational design when considering commercial and private human access to space.

Limitations. While this design is conceivable, critical consideration about feasibility and a proof-of-concept is required before its implementation in space. Foreseeable limitations with this design include establishing a differential feedback transduction system design for non-prosthetic users and ergonomic considerations for loading suits. Unlike prosthetic users, non-prosthetic users require a biosensor and feedback system, which accounts for an intact limbs and surface EMG detection from different motor units in contrast to prostheses designs which consider the most distal EMG signal as input. Moreover, surface EMGs are limited by signal noise, when compared to needle electrode and fine-wire EMGs, which are often classified as gold standards for signal detection for diagnostic purposes. There additionally exists the need to design accelerometers and prosthetics tailored to individuals, which may not be economical in the context of resources and costs, especially for large-scale space flights or missions.

Conclusion: The conceived use of prosthetic accelerometers for restoring controlled and normal limb movements under microgravity conditions in space is feasible; however, there is a need to develop an inclusive design for prosthetic and non-prosthetic users, as well as demonstrate a proof-of-concept for this model before its implementation.

APPLICATION OF ELASTIC COMPRESSION BANDAGES TO PREVENT ORTHOSTATIC HYPOTENSION FOLLOWING EXPOSURE TO MICROGRAVITY CONDITIONS. P. A. Johnson\textsuperscript{1,2}, R. Witiw\textsuperscript{1} and A. A. Mardon\textsuperscript{2}, \textsuperscript{1}Department of Medical Sciences, University of Alberta (email: paj1@ualberta.ca) \textsuperscript{2}Antarctic Institute of Canada (103, 11919-82 Str. NW, Edmonton, Alberta CANADA T5B 2W4; email: aamardon@yahoo.ca)

**Introduction:** Nearly all astronauts experience orthostatic intolerance after space flights with about 20\% experiencing syncope or presyncope after landing. Apart from loss of consciousness associated symptoms include dizziness, vertigo, blurred or tunnel vision, nausea, headache, or sweating. The underlying cause of these conditions is the sudden shift from microgravity conditions to gravity on a celestial body – a common phenomenon in several space flights. Microgravity induces hypovolemia, a condition where astronauts lose a great deal of their blood volume and thereby influence orthostatic tolerance.

There have been several proposed physiological mechanisms for this body fluid volume loss in microgravity conditions. One widely accepted theory suggests the reduction of a relatively unidirectional gravitational pull enables an increased fluid filtration in the upper body interstitial spaces. Another theory puts forward the peripheral vascular resistance becomes ineffective in microgravity such that there is an imbalance in perfusion leading to a lower preload to the heart. Disregarding this mechanism however, hypovolemia will result in cardiac atrophy which weakens the heart and ultimately results in lower blood pressures affecting the orthostatic balance.

**Management of orthostatic intolerance:** Orthostatic hypotension is not exclusively a condition affecting astronauts. In fact, it is a common condition in the elderly and those with affected by certain hereditary or non-hereditary cardiovascular conditions. Moreover, there have been several potentially utile proposals for management of orthostatic hypotension in space flights. Currently, the most mentioned treatment on space flight are pharmacological interventions.

The application of compression bandages in the management of orthostatic intolerance is no novelty. In fact, its use is mundane in the elderly to prevent progressive orthostatic hypotension, which is an increasingly common occurrence in the geriatric population during standing. Lower limb compression bandages, in particular, have been demonstrated to be effective in avoiding orthostatic blood pressure reductions. In a study conducted by Podoleanu \textit{et al}, compression pressures ranging from 40 to 60 mmHg utilizing elastic compression bandages in a cohort of patients showed a significantly lower decrease in pressure when compared two different cohort: one without any compression bandages and another with abdominal compression bandages. Moreover, long-term compression stockings therapy is feasible and common for both elderly and patients with venous disorders such as deep vein thrombosis, edema and inflammation of the veins.

**Proposed design for space flights:** Prior to and throughout the duration of space flights, the authors propose that compression bandages can be adjusted and used to maintain physiological pressures within the body. These modifications would have to account for the microgravity-associated hypovolemia and increased blood loss in the upper body, which suggest the utilization of lower limb compression bandages alone may be ineffective and there is a hidden utility for abdominal or perhaps even upper extremity compression bandages in space flights. A clear advantage in the implementation of compression bandages is its focus on prevention as a means of management instead of treatment after orthostatic intolerance is observed, as is the case with a multitude of pharmacological treatments. In light of economic considerations, compression bandages are both resource-efficient and low-cost. While immensely promising, its conceived use relies extensively on certain underlying assumptions which must be accounted, for feasibility.

**Limitations.** Perhaps the most critical consideration is its feasibility and lacking evidence in a healthy cohorts where a clear distinction exists in demographic used in current bodies of literature. An exceedingly large number of studies examine orthostatic hypotension in populations of elderly or patients with cardiovascular complication. This suggests the external validity of these studies are weak and require further exploration before its appraisal for space missions. Other potential limitations in this study include the influences of compression bandages on the mobility of astronauts in space flights and its low quality of ergonomics which may create discomfort reducing compliance.

**Conclusion:** The modification, development and use of compression bandages as an alternative form of management of orthostatic intolerance is conceivable; however, there are a few practical limitations warranting further research before its implementation.


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The recent push by NASA and the US government to increase sustainable human presence on Lunar surface heavily relies on the application of In-Situ Resource Utilization (ISRU) techniques. One of the most valued resources on the Moon is water. The water has application ranging from fuel or propellant production to human consumption. A hindrance to lunar mining has been that the uncertainty related to the assessment of the volume and characterization of water-ice. The orbital estimates of the quantity, distribution and composition of the water-ice varies widely based on the analysis of available information. Exploration drilling at target sites is critical to establishing the ground truth for planning the future extraction or mining activities.

The goal of the current study is to analyze the drilling systems developed by NASA and other agencies for extraterrestrial exploration, design a drilling rig to replicate the operations of these drilling units, and develop a pattern recognition algorithm that analyzes real-time high-frequency drilling data and estimates the subsurface geotechnical properties. This work is based on the analytical and data-driven models developed by the drilling industry to characterize subsurface formations based on drilling parameters. This work builds up on existing models to apply them to an auger based rotary drilling system. Figure 1 shows the drilling unit developed to conduct drilling tests.

This paper will discuss the results from the initial drilling tests, conducted on homogenous analog grout samples to replicate one of the expected lunar subsurface conditions. The high-frequency drilling data was filtered to remove the drilling noise and correlated to the lab tests to find distinct patterns of various drilling parameters related to strength of the media being drilled. Figure 2 shows the mechanical specific energy recorded through different boreholes in the first block. Just based on drilling data a layer of harder formation was detected and tracked across the borehole. Further analysis of the drilling data also revealed the problem with hole cleaning and removal of the cuttings. It showed that the drilling auger used in testing was inefficient in removing cuttings below 250 mm of drilling depth.

Figure 1: Test drilling rig

Figure 2: tracking mechanical specific energy across boreholes revealed a harder layer in the grout block and a cutting transport problem around 250 mm depth

The recorded high-frequency drilling data will be used to assess the relationships between various material properties and drilling parameters for real time assessment of geotechnical units being drilled. The pattern recognition algorithm being developed can enable cost-effective exploration of water-ice resources on Moon and Mars and real time generation of information on material strength. This is the key component for development of the ground profiles, and proper preparation of the exploitation plans.
MINI-RF MONOSTATIC RADAR OBSERVATIONS OF PERMANENTLY SHADOWED CRATER FLOORS. L. M. Jozwiak¹, G. W. Patterson¹, R. Perkins², ¹Planetary Exploration Group, Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA, ²Department of Earth and Environmental Sciences, Wesleyan University, Middletown, CT, USA (lauren.jozwiak@jhuapl.edu).

Introduction: The identification of water in the polar regions of the Moon has been a significant finding for both the lunar scientific and exploration communities [1, 2]. Following the Lunar Crater Observation and Sensing Satellite (LCROSS) experiment impact into Cabeus crater [3], efforts were made by several other instruments to identify the source of the water observed in the impact plume [4]. Water ice has the diagnostic characteristic of a circular polarization ratio (CPR) > 1, and as such, should have been readily identifiable in Mini-RF data. However, observation of both Cabeus crater and the LCROSS impact site itself by the Mini-RF instrument revealed circular polarization ratio (CPR) values comparable to, or lower than the surrounding south polar terrain [5]. This observation suggested that, if present, the water ice must be in the form of small (< ~10 cm), discrete pieces of ice distributed throughout the regolith, or as thin coating on ice grains.

Since that time, evidence has grown for the presence of water ice (of some form) located in the permanently shadowed regions (PSR) of the Moon [6, 7], and the continued operation of the Mini-RF instrument has allowed for the production of high-resolution polar mosaics of the CPR data. These polar mosaics have allowed for an expanded analysis of CPR values for multiple permanently shadowed craters at both the north and south pole of the Moon.

PSR Crater Analysis: This analysis focused on comparing the radar response of permanently and non-permanently shadowed regions of both north and south polar lunar craters. The analysis regions were constructed using LOLA-based shadow models and LOLA-based slope maps. Because sloped surfaces (such as crater walls or peaks) can result in spurious additions to the returned radar signal, we restricted our analysis to regions with slope less than 5°. These flat regions were then divided into permanently shadowed and non-permanently shadowed regions using the shadow model. Finally, we considered only craters where both the flat permanently and non-permanently shadowed regions were spatially expansive enough to be considered significant.

Our final dataset included 10 north polar craters and 11 south polar craters. Using Mini-RF monostatic polar mosaics generated by the USGS, we used the generated shapefiles to extract CPR values for the permanently and non-permanently shadowed flat crater floor regions. Comparing the distribution of values for the PSR and non-PSR of each crater reveals similar distributions with subtle variations. To better assess the statistical variability of the signal, we plotted the mean ± 1 standard deviation for both the PSR and non-PSR crater floor regions, shown for the north polar craters in Fig. 1. While the majority of the PSR and non-PSR regions have different mean values, when the standard deviations are included, none of the PSR regions are statistically distinct from the non-PSR regions. Specifically, none of the PSR regions show significantly higher CPR returns, as would be predicted for radar interaction with water ice [e.g. 8].

Conclusions: These results are consistent with the results of Neish et al. [2011] [5], and suggest that the water ice present in the permanently shadowed regions of lunar polar craters is unlikely to be present in the form of thick, pure ice deposits. The ice instead, must be confined to small, discrete blocks, or thin coatings on rock grains. Additionally, water ice does not appear to be preferentially concentrated in permanently shadowed regions.

These results are significant for future ISRU efforts in that they suggest that water ice deposits might be equally accessible at thermally stable depths in non-permanently shadowed polar regions.


Figures:

Figure 1: Mean CPR values +/- 1 standard deviation for the analyzed north polar permanently shadowed crater floors. CPR values derived from Mini-RF east-looking mosaics.
**PARAMETRIC REVIEW OF REGOLITH EXCAVATION AND HANDLING TECHNIQUES FOR LUNAR IN SITU RESOURCE UTILISATION.**

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**Introduction:** In recent years the exploration of the Moon and the establishment of a permanent human presence on its surface has regained the attention of space agencies, for example NASA recently announced a partnership with nine companies for commercial lunar payload delivery. There are various scientific rationales for returning to the Moon, ranging from investigating the origin and evolution of the Earth-Moon system, to life sciences and using the Moon as a platform for Earth and astronomical observation [1]. To establish a sustained lunar surface infrastructure and support extended exploration activities in cis-lunar space, the use of native resources is seen as vital. Such In situ Resource Utilisation (ISRU) will drastically reduce initial launch mass and cost, and decrease the reliance on supplies from Earth [2].

The use of lunar regolith: The Moon’s surface is covered in several meters of soil (regolith) created by the impact of asteroids, comets, and their debris over 4.5 billion years of Solar System history [3]. The regolith contains several chemical elements that can potentially be used for mission support; for example, more than 40% oxygen that can be used as propellant and in life support systems, forming the most likely initial applications [4][5]. Several techniques for oxygen extraction from regolith have been proposed and are being investigated, e.g. hydrogen or carbo-thermal reduction [6][7]. The lunar soil can, however, also be used for in-situ manufacturing and habitat construction. A range of technologies are being developed at the moment, including: sintering of regolith using concentrated sunlight [8], 3D printing for building habitats (D-shape) [9], selective laser melting [10], and direct energy deposition [12]. Other applications include radiation protection, metal production, or the extraction of solar-wind implanted volatiles.

Excavation, handling, and beneficiation of regolith: All ISRU processing techniques have the mutual requirement of having (pre-processed) regolith delivered constantly. Therefore, efficient and reliable excavation, handling, and beneficiation processes of regolith have to be established. Even though many possible extraction options are being investigated, e.g. bucket wheels/ladders [13], pneumatic systems [14], (flexible) augers [15], or scrapers [16], there is currently no consensus as to which option is optimal for different lunar surface conditions or manufacturing needs. One significant issue to consider is the geotechnical properties of the lunar regolith, which differ significantly from terrestrial soils. Regolith is highly abrasive due to extremely irregular particle shapes, very fine-grained, adhesive, dense, and easily electrically charged [17]. Experience gained during the Apollo missions showed that the lunar “dust” damages surfaces, coats and penetrates into mechanisms, causing malfunction of mechanical parts or thermal control problems [18]. Therefore, any ISRU hardware that is supposed to operate for an extended period of time, has to be specifically designed to withstand the impact of these soil properties. In order to design robust mechanisms and test them on Earth, we need new sample return missions obtaining larger quantities of natural regolith.

Parametric review of excavation and handling techniques: The present work provides a comprehensive review of regolith excavation and handling techniques for lunar ISRU. To compare and evaluate the different mechanisms, a set of representative parameters is chosen. Additional to process parameters, e.g. excavation rate or power consumption, experimental conditions, type of simulant used, and gravity conditions are being considered. Based on the parametric comparison of the mechanisms the probability of incorporation into future lunar ISRU missions is evaluated. This will enable easier categorisation and evaluation of future excavation technologies.

**References:**

Open-source AI Assistant for Cooperative Multi-agent Systems for Lunar Prospecting Missions. Z. M. Kakish1, F. R. Lera2, D. Bischel3, A. Mosquera4, R. Boumghar5, S. Kaczmarek6, T. Seabrook7, P. Metzger8, J. L. Galache9. 1Arizona State University (zahi.kakish@asu.edu), 2University of Leon (ffrod@unileon.es), 3University of California Santa Cruz (dbschel@ucsc.edu), 4Aten Engineering (ana@atenengineering.com; jl@atenengineering.com), 5European Space Agency (redouane.boumghar@esa.int), 6Imperial College London (s.kaczmarek17@imperial.ac.uk), 7Oxford University (timothy.seabrook@cs.ox.ac.uk), 8University of Central Florida (Philip.Metzger@ucf.edu).

Introduction: In recent years, we have seen a major turning point in the development of Space exploration capabilities. Government Space agencies are achieving great milestones in this NewSpace race by mixing and assisting commercial ventures. All these advances, and humanity's inherent hunger for adventure and exploration, are pushing forward the development of the space sector in an exponential way, helping envision a near future with settlements on the Moon and Mars. For this dream to come true, and establishing permanent presence in space, in-situ exploration, identification, and prospecting of space resources is paramount to sustain human activities. Mining water, for example, will be essential for life-support systems, and can, additionally, be split and used as rocket propellant. If carbon is found in water-ice, as it’s believed to exist, it can be transformed into plastics that can be used to protect against radiation, and other minerals can be targeted with the goal of construction.

Just a few months ago, two missions successfully reached their final destinations after their many year long pursuits: JAXA's first pair of hopping robots called MASCOT [1] on a nearby asteroid, Ryugu, and NASA/JPL's Mars lander InSight [2]. In the case of the MASCOT robots, mission planning for non-terrestrial surfaces is critical to a mission's success [3]. Future public and private mission's would seek to expand rover and other robotic platforms for exploration and scientific research, but numerous issues persist.

At present, robots missions are expected to do a wide variety of tasks ranging from exploring, prospecting, and research. These tasks are made evermore difficult by communication interference, interactions with human operators in the loop, and harshness and unpredictability of the environment, just to mention a few. These challenges can be significantly reduced by multi-robot operations, which can improve the mission efficacy and lower the risks by autonomously coordinating the agents. Despite there being many advances in the field, there are still numerous challenges to reduce the complexities associated to the coordination of multi-robot systems and mission planning strategies, which motivates further research.

During work at the NASA Frontier Development Lab [4] (an AI accelerator geared towards space applications), the authors have put forward a stepping stone towards that goal in the form of MARMOT, or Multi-Agent Resource Mission Operations Tools. MARMOT is an extensible, open-source tool that allows users to expand the current functionality of mission planning systems for extra-terrestrial operation. The first iteration of the tool provides heterogeneous multi-agent global planning optimization of environments for different tasks and goals. Future iterations of the work will allow extensibility into other areas of machine intelligence and robotics, and further enhance the goals both public and private space operations.


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Introduction: OffWorld is building millions of smart robots working on the human supervision on earth and in space, turning the solar system into a habitable place for life and civilization. Enabling human expansion off our home planet is the most important objective of our civilization, for three reasons:

- species level life insurance policy,
- sustainable development on earth,
- opening up the new frontier.

What we absolutely require in space is a robotic workforce for tough jobs. We need to be able to excavate underground habitats and extract water ice and materials. From the collective volatile’s we need to make drinkable water, breathable air and rocket propellant. In order to sustain expansion we need to be able to manufacture basic structures and solar cells so that we can produce unlimited power. Ultimately, these systems will need to replicate themselves for rapid and economic expansion. In order to do this, we need to emulate the entire infrastructure value chain from mining, processing, fabrication, assembly and construction. However, we cannot just export current Earth-based practices and technology. We must reinvent how we undertake these processes here on earth, and transfer them directly to the expansion of civilization into the solar system.

OffWorld has undertaken extensive Research and Development in the field of extreme environment industrial robotics initially applied to the mining and processing sector. The objective is the establishment of an end to end collaborative robotic system comprising of hundreds or even thousands of multi-species robots working together with internal and collective autonomy to achieve defined strategic objectives.

With the ongoing input of mining industry expertise on a daily basis, OffWorld has developed its robotic systems hand in hand with leading edge knowhow from the mining sector. Initially, we developed baseline systems analysis tools for modelling a variety of scenarios with our robotic architecture, including the objective of rapidly deploying them for space based operations.

Key to the future of operations in space is the ability for robotic systems to undertake multiple complex tasks autonomously and with minimal human intervention. OffWorld has been developing a task agnostic machine learning framework to address and optimize any industrial process. This revolutionary approach to minimally supervised autonomy ushers in a new era of remote operations in extreme environments such as the Lunar or Martian surface. We are already developing the first suite of machine learning agents.

OffWorld proposes to mature our regolith to gaseous oxygen and gaseous hydrogen subsystem using six distinct processes: 1) volatile extraction, 2) water distillation, 3) water vapor superheating, 4) water dissociation, 5) oxygen separation and 6) hydrogen separation. Each process is envisioned as a stand-alone function within an autonomous robotic platform. Our autonomous robotic platforms are currently in development for Earth mining under internal funds with demonstration units planned for testing later this year. Our ISRU Technology subsystem is a subset of OffWorld’s overall concept for mining Moon and Mars regolith for volatiles and minerals in addition to processing, manufacturing and construction robots within the same robotic platform.

Our subsequent goals in near-Earth space for the expansion of this modular toolkit are to enable the formation of in-space vehicles, transport, depots and facilities, and orbital workshops for the autonomous recovery and re-utilization of space debris as a resource. Once our machine intelligent robotic system has mastered lunar surface and in-space operations, we will expand their utility to near Earth asteroids and the Martian surface, leveraging lessons learned to enable the expansion of humanity into the solar system.

Introduction and Rationale: Before ISRU can be prudenty incorporated into the exploration architecture, the resources need to be assessed in a transparent, unbiased, and quantitative manner. Creating such assessments is the responsibility of the US Geological Survey.

Although some aspects of the USGS quantitative resource assessment methodologies differ between water, energy, and minerals assessments, the basic approach is the same. In the assessment context, a resource is defined as a concentration of material or energy in such form and amount that economic extraction of a commodity is currently or potentially feasible. USGS resource assessments report (1) boundaries delineating the spatial extent of resource occurrence, (2) the statistical distributions of resource size and quality, and (3) estimates of the total number of occurrences for spatially discrete resources such as mineral deposits or portions of the study area or volume within which the resource exceeds a defined minimum quality for spatially continuous resources. The results of these three steps are combined to yield a quantitative estimate, with uncertainties, of the total identified and undiscovered resource.

The applicability of the 3-part USGS quantitative mineral resource assessment methodology to asteroids was demonstrated in 2017. A similar study has been initiated for the Moon, with an initial focus on solar energy, bulk regolith, and ice.

Assessing Lunar Solar Energy: Our understanding of the nature of solar energy and the technology to extract it are mature. The quantity of extractable solar energy is tied to our knowledge of (a) the ephemerides of the Moon and Sun; (b) lunar topography; and (c) technologies for converting solar energy to electricity. The relative motions of the Moon and Sun are known to exquisite precision and accuracy. The interaction with lunar topography is directly observed via insolation maps. The technology to extract energy from sunlight is at TRL10 with well-known costs.

Assessing Lunar Regolith: We have a firm understanding of the impact gardening process that creates regolith. We have excellent in-situ data from the Apollo missions and useful additional data from robotic landers. This allows us to use a variety of global remote sensing data sets to map out key properties of the regolith, such as thickness, petrology, and boulder abundance. This state of knowledge is well-suited to the USGS resource assessment methodology. There are many potential uses for the lunar regolith, including being a source of oxygen or the main ingredient in concrete. To limit the scope of the initial study, we plan to focus on the use case of simply bulldozing regolith over a habitat for micrometeorite shielding.

Assessing Lunar Ice: Water, especially in the form of ice in polar cold traps, is the most desirable lunar resource. However, a quantitative assessment of lunar ice is currently impractical because critical information is missing. Still, the USGS mineral resource assessment methodology can be used to lay out a methodical campaign that would allow future data-driven decisions related to ISRU of lunar ice.

Before the USGS mineral assessment methodology can be applied, it is necessary to develop “descriptive” models of the key characteristics and physical/geological processes that created the deposits. Therefore, the first step toward an assessment would be a mission that directly interacts with the ice in at least one location and obtains fundamental observations such as a vertical profile of the ice concentration and the detailed composition of the ice and its contaminants. With development of deposit models, the next part of the resource assessment is to identify “tracts” where the deposits could plausibly exist. For example, DIVINER temperature maps can already be used to map, to first order, locations where shallow subsurface ice can be stable for a billion years. Next we need a probabilistic estimate of the number of deposits within the tracts. This may be possible to accomplish with orbital remote sensing, especially if the ice deposits are created by processes that act over very broad geographic regions. The third part of the assessment is to measure the sizes and qualities of a statistically relevant number of deposits. If the deposits are relatively homogenous, this could require simple in situ measurements at only about a dozen sites. However, if the nature of the ice proves to be more complex, missions with mobility and/or drilling will be required. In either case, the end product would be mathematical expressions describing the probability distribution functions of the size and quality of the deposits. These are combined with the number densities developed in the second part to estimate the total ice resource.

Framing the entire assessment process is the evaluation of ISRU technologies to create an economic model that identifies the cost of extracting water from the lunar regolith. With this suite of information in hand, commercial and governmental decisionmakers can make informed decisions on how to pursue industrial-scale ISRU of lunar polar ice.
**Introduction:**

The Republic of Korea is currently conducting strategic and systematic researches on space exploration. Under the Governmental supports, recent success of launch vehicles by Korea Aerospace Research Institute (KARI) is the clear evidence for further program in space exploration in Korea. For the lunar exploration and Mars exploration, recently, the private sector is also trying to participate in space exploration. In the late 1950s, the international community had just witnessed the space arms race with, both, the US and Soviet Union launching rockets to the moon. Following 9 more rocket launchings, the 3-stage rocket ‘IITA-7 CR including a small camera and a rat with wireless health monitoring’ took off successfully in 1964.

As a private approaches for space exploration in South Korea, Inha Institute of Space science and Technology (Inha IST) was established and started the internationally cooperative research works with a NASA Langley Research Center (NASA LaRC). Also, recently new organization from Inha University, the Inha Research Institute for Aerospace Medicine and medical school also jointed for space exploration.

**Potential ISRU Activities**

Based on these activities, now new approaches for space exploration is under prepared for lunar exploration. Currently Inha IST and Korea Institute of Geoscience and Mineral resource (KIGAM) agreed to collaborate and join the activities for lunar exploration with NASA LaRC.

Based on the technical discussion with NASA LaRC, Inha IST has found many potential area to join the current ISRU program with KIGAM.

The first possible collaborative topic will be the air-tighten fabric technology to contain oxygen or hydrogen gases for habitation or propellant usages. For this, light and strong fabric with the anti-cosmic ray protective function will be required. Also, to protect anti-dust function landing pad in Moon or Mars will be the other possible area to work together with NASA LaRC.

Second issue will be the water extraction and purification with membrane technology. Also further chemical process for propellant conversion will be connected to this water technology. This topic will be cooperative with KIGAM by planetary resource investigation.

Third one will be energy harvesting on Moon to generate energy with KIGAM based on the elementary map. Resource extraction technology, based on novel energy harvesting technology from the charged lunar surface by electro static conversion system, will be investigated.

The last one will be related to the space medical issue on Moon. Inha Research Institute for Aerospace Medicine and Inha medical school will assist and join the basic biological (including animal test) as well as fundamental life science investigations to understand human safety issue in space habitation and travel.

**Way Forward**

Currently, the attendance of team Korea in the Moon Race is under preparation. The moon race will be the best implementing opportunity to join the lunar exploration from South Korea.
POSSIBLE FE-METAL ENRICHMENT AREAS IN THE SPA BASIN  

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Introduction: Several enigmatic structural and petrologic features of the Moon are widely discussed: origin and global spreading of the high-Ti lunar basalts, mascons, swirls. The Moon moves away from Earth. Loosening its angular momentum due to slowing rotation a necessary compensation is fulfilled by sending dense materials into the crust. Varying density basalt flows (high, low, very low-Ti) reflect various stages of the slowing rotation process. Various contents of dense mineral component – ilmenite in basalts means various densities of the rock. Iron in basalts can be in less dense dark minerals and denser ilmenite thus influencing overall basalt densities corresponding to requirements of “healing” diminishing angular momentum. Spectral mapping of basalt types [6] indicate that for large parts of Oceanus Procellarum younger basalts are more titanium rich than the older basalts, thus somewhat reversing the trend found in the returned samples [5]. In some smaller basins spectral mapping also shows titanium richer basalts being older than titanium pure ones [4]. Thus, one may conclude that decreasing rotation rate of the Moon was not smooth but rather uneven. The deepest SPA Basin must be filled with denser rocks than the shallower Procellarum Ocean filled with basalts and Ti basalts. The Clementine spectral data show presence of orthopyroxene and absence of plagioclase [7] favoring some dense ultrabasic rocks. An obvious tendency to approach this type of rock would be to observe it in the Luna 24 samples from also very deep (up to 4. 5 km) Mare Crisium. In fragments there prevail pyroxene and VLT-ferrobasalts (Mg-poor). Unusual melt matrix breccia with globules and crystals of Fe metal were also found [1]. Among glass droplets there 40-54 % are irons. Nearly half of the black and brown droplets have either vesicles or iron droplet trains or both [1, 2]. A significant portion of Mg enriched fragments in the Luna 24 soil is also observed. The lunar global magnetic map (Fig.) favors a conclusion about some important Fe metal admixture increasing not only magnetism but also overall rock density of the deepest Basins and Mares. An association of Mg-pyroxene enstatite with Fe-Ni metal is well known in cosmic materials (for an example, E-chondrites). On the Moon enigmatic but characteristic swirls with high albedo, elevated magnetism and diffused boundaries could be presented by this type of high-Mg (light in color) with Fe metal rock. The SPA Basin is one of the enriched with swirls relatively magnetic areas (Fig.) [3]. Another deep in relief and relatively magnetic is the Mare Crisium area. In the Reiner Gamma swirl area some small rifts are detectable. The SPA Basin as a part of the lunar tectonic triad having the largest geoid anomaly in some places shows spectral geochemical signs of the highland rocks [7, 8]. They are exposed “windows” of these rocks revealing a real basement of the deeply subsided SPA Basin. A significant part of the basic-UB infilling of the SPA Basin could be presented by the above mixture (Mg-silicate + native Fe). Metal iron is an important component of the constructive materials for the Moon and Cosmos investigations. The Chang-4, if successful, will bring new facts for the lunar sciences [9, 10].

Fig. Lunar magnetism [3]

A COMPREHENSIVE RISK ASSESSMENT OF THE PROPOSED NASA LUNAR ORBITAL PLATFORM-GATEWAY. M. Lacerda¹² and D. Park²¹ NASA – National Aeronautics and Space Administration - Ames Research Center (michel.usp@gmail.com), ² School of Aerospace Engineering, Georgia Institute of Technology (mal7@gatech.edu).

Introduction: This study presents a comprehensive risk assessment of the proposed NASA Lunar Orbital Platform Gateway. Planned for 2024, the Gateway is a platform that will orbit the cislunar space to serve as a bridge for manned missions to the moon surface. It was proposed by NASA and stated as a priority with a 2024 start date by the President of the United States. This Study will perform a detailed risk assessment of the main element of the Gateway and the different levels of risk that it presents to the manned missions, its hardware and its occupants.

The Gateway[1] will be composed of the following elements: Power and Propulsion Element, European Service Module, International Habitation Module, Robotics, U.S. Habitation Module, Logistics Resupply, Multi-purpose Module, Orion Crew Module and Orion Service Module. NASA plans to begin operations of its Gateway in 2024 with assistance of different international partners. Its operation will be performed on cislunar orbit by astronauts and by Mission Control on Earth. The figure 1 shows the planned Gateway platform. The figure 2 shows a mockup of the Habitat module of the Gateway.

Figure 1: NASA Lunar Orbital Platform Gateway[1]

The conjunction of different factors such as the radiation characteristics of the cislunar space[2], the microgravity, the assembly and the human operation of that platform makes the case for this study. The Risk Assessment of the Gateway includes several risks by different stakeholder, occupants, assemblers, manufacturers and environmental agents as well.

. The figure 3 shows the radiation on the International Space Station as an example of environmental hazard.

Figure 3: Environmental Hazard: Radiation on the International Space Station[2]

Overall, this study presents a comprehensive risk assessment of the NASA Gateway to begin operations in 2024 to pave the way to manned missions to the surface of the moon.

References:
The Luxembourg Perspective on ISRU and the Development of a Commercial Space Ecosystem

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Abstract

In 2016, Luxembourg launched the SpaceResources.lu initiative with the long-term vision to enable the exploration and utilization of space resources with the aim to contribute to the peaceful exploration and sustainable utilization of space resources for the benefit of humankind. One important objective is to diversify the Luxembourg economy by creating a sustainable commercial space ecosystem. To kick off the initiative the country identified an envelope of 200 M Euros to support all aspects of the strategy. In 2017, Luxembourg passed legislation that enabled the creation of a regulatory framework to allow businesses to harvest and use space resources. The framework also helps decrease risks in the emerging space resources industry for investors. In September of 2018, Luxembourg announced the creation of the Luxembourg Space Agency (LSA). These actions illustrate the strong determination of the country to reach their long-term vision of developing a sustainable commercial space sector.

The primary motivations of the Luxembourg SpaceResources.lu Initiative is to support the existing local space industry, attract leading space companies, while creating a nurturing environment for start-ups and new space endeavors. Five strategic pillars provide the foundation of the Space Resources initiative:

• Promote space resources by ensuring national political support and promoting international cooperation.
• Build a regulatory framework by establishing a clear legal framework and engaging internationally.
• Develop top-tier talent by promoting long-term public support and workforce engagement through education and R&D.
• Offer R&D assistance by providing dedicated support for industrial research and development activities.
• Enable long-term investment by developing financial instruments focused on commercial space.

This presentation provides an overview of the status of the activities undertaken by the Luxembourg Space Agency to support each of the 5 Pillars in the strategy and provides details on the progress it has made. In addition, a high-level summary of the recent ISRU Value Chain Study and the Mining Space Summit 2018 will be discussed.
Introduction: The Space Instrumentation Group at The Open University are investigating microwave sintering of lunar regolith/simulant as a potential fabrication method of 3D printing on the Moon to build lunar habitats. This has enabled us to integrate our existing expertise in 3D Concrete Printing [1, 2] and knowledge of lunar science and ISRU potential on the Moon [3] to perform a series of microwave sintering experiments aiming to develop a potential fabrication method of an extra-terrestrial construction process.

As part of this initiative, we have designed an industrial bespoke microwave heating apparatus. This apparatus will allow a thorough experimental investigation of the sintering mechanism of lunar regolith/simulant in the cavity. The mechanical properties of sintered specimen produced under optimal conditions can then be explored. The experiment will also be validated using COMSOL Multiphysics simulation software. In this contribution, we discuss the first outcomes using the bespoke microwave heating apparatus, and how COMSOL has been employed to understand the different characteristics of lunar simulants when subjected to microwave heating.

Microwave sintering: Microwave sintering of lunar regolith as a potential fabrication method of lunar habitat construction has become one of the favourite topics in recent years [4]. Previous research in this area, however, have been conducted using domestic microwaves, which are not ideal for sintering lunar simulants due to (i) incapable of withstand temperatures of up to 1,250 °C – the melting point of lunar regolith/simulant; (ii) not optimised to maximise microwave energy into a single hotspot; (iii) unable to mimic lunar atmospheric condition; (iv) it is not possible to measure sample surface temperature accurately; and (v) the fixed frequency at 2.45 GHz which is an optimal frequency to heat water molecules in food products but may not be optimal for inorganic solid materials such as lunar regolith.

Thus, an industrial bespoke microwave heating apparatus has been designed to overcome the current limitations. Figure 1 illustrates a design of the apparatus which includes two pyrometers, one viewfinder window, and a cylindrical cavity with a flange for a vacuum pump. The ports can also be connected to a mass spectrometer, permitting extraction and analysis of volatiles while specimens are heated. Volatiles in regolith can be extracted by heating the regolith between 300 and 900 °C [3, 5]. For example, a temperature of 700 °C is sufficient to obtain most of the H2 and He [6]. Thus, the apparatus could also be used for measuring the types and amount of volatiles which could be used for propellant and life support (e.g. water). The new apparatus would allow to (i) maximise microwave energy in a single hotspot; (ii) measure the surface temperature and phase change of specimens under a near lunar atmospheric condition with more accuracy, and (iii) heating specimens of lunar simulant rapidly to be sintered/melted. This first version of the apparatus does not support multiple frequencies; however, this feature is planned to be added in a future upgrade.

Figure 1: Bespoke microwave heating apparatus

Numerical Modelling: As complementary research of the lab-experiment, we have chosen COMSOL (version 5.3a), which has been used previously for a similar purpose [7]. COMSOL requires various parameters of material characteristics to simulate microwave heating phenomenon. The findings from the numerical modelling are (i) verifying the bespoke design of the cavity that could maximise microwave energy to heat specimens; (ii) understanding the sequence of sintering phenomenon by continual simulation of the surface and internal temperature of specimens; and (iii) identifying the different effects of sintering among frequencies in terms of the time and penetration depth.

References:
The Metalysis-FFC-Cambridge process for the efficient production of oxygen and metals on the lunar surface.
B. A. Lomax¹, M. Conti², N. Khan², M. D. Symes¹; ¹University of Glasgow, UK; ²Metalysis, UK.

Introduction: Oxygen will undoubtedly be one of the most valuable resources in a self-sustaining space economy. As the largest weight component of any bi-propellant rocket, an efficient and plentiful source of liquid oxygen (LOX) on the lunar surface would reduce the reliance on mass transported from Earth. In-space lunar refueling would impact not only lunar surface operations, but also activities in cis-lunar space, and deep-space missions.

While evidence is growing for ice deposits in the permanently shadowed craters at the lunar poles [1], the form, quantity, and accessibility of this resource remains unknown. The lunar regolith, on the other hand, is ubiquitous across the entire lunar surface and contains 40-45 wt% oxygen. Additionally, the lunar regolith contains a range of other elements that can be used to produce useful metals and alloys in-situ. Developing a single process that can efficiently extract the oxygen from regolith and produce useful materials will have a significant impact on the space resource economy. In this scenario, a process capable of both could operate synergistically with water extraction operations, should the lunar ice deposits prove to be a viable resource for oxygen. Furthermore, technology developed on the lunar surface that can produce metals and alloys is applicable to future Mars mission architectures, where processes that only produce oxygen become redundant in favor of simpler methods utilizing the Martian atmosphere.

The FFC-Cambridge process: The Fray-Farthing-Chen (FFC)-Cambridge Process has been suggested as an efficient method for the production of both oxygen and useful materials from lunar regolith. The FFC-Cambridge process was invented at the end of the 1990s as a direct electrochemical method for producing metals from the corresponding metal oxides in molten salt [2]. At temperatures where the CaCl₂ salt is molten and can facilitate the transport of ions, approximately 900 °C, the metal oxide feedstock remains in the solid state throughout the entire process.

The metal oxide, which in the past has been in the form of a sintered pellet, forms the cathode and is electrochemically deoxidized to produce metal and oxygen ions:

\[
\text{Cathode: } \text{MO}_x + 2xe^- \rightarrow M + xO_2
\]

In the terrestrial context, a carbon-based anode facilitates the removal of oxygen from the system in the form of carbon dioxide and carbon monoxide. In the lunar context an inert anode can be employed to directly produce oxygen:

\[
\text{Anode: } 2O_2^- \rightarrow O_2 + 4e^-
\]

Some previous work has been done to investigate the reduction of lunar regolith using the FFC-Cambridge process [3]. The primary focus of this was the utilization of lunar ilmenite as a feedstock; however, this process is distinguished by the fact it has the ability to remove 100 % of the oxygen from lunar regolith in the solid state, regardless of composition. Additionally, in the early years of this technological innovation, many aspects that would be relevant to a large-scale lunar operation were not yet proven.

Recent developments: In the almost two decades since this novel process was first reported, significant progress has been made in developing this technology. Metalysis (UK) have successfully scaled-up and commercialized the production of a number of metals and alloys. Innovations in the process have been made to allow for the production of metal powders for additive manufacturing, aerospace and automotive applications directly from powder oxide feedstock.

Current work: The current research investigates the reduction of lunar regolith with the FFC-Cambridge process, applying the processing innovations of the Metalysis. Maximizing efficiency, in terms of quantity of oxygen extracted and the functionality of materials produced versus energy consumption and process complexity are key goals. The processing knowledge gained in the years of terrestrial technology development will inform the design of a process that has the ability to be scaled up and operate sustainably and autonomously on the lunar surface.


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In-situ Resource Utilization for Construction and Hardware Manufacturing to Support Lunar Exploration – Developments at ESA. Advenit Makaya1, 1Materials and Processes Section, ESTEC, European Space Agency, Keplerlaan 1 - PO Box 299, 2200 AG Noordwijk-ZH, The Netherlands. Corresponding author: advenit.makaya@esa.int.

An overview of completed and on-going activities, funded by or conducted within ESA, will be presented, reflecting the development of technologies for the processing of lunar regolith, for construction and hardware manufacturing. These technologies are intended to help develop the necessary infrastructure and equipment, to enable exploration activities and to support the construction, operation and maintenance of a settlement on the lunar surface.

Activities to be presented include the processing and characterization of structural materials, with or without binder, for additive manufacturing of structures and hardware at various scales. Produced items cover habitat construction, maintenance parts and power generation applications.

References:
CHEMICAL EFFECTS ON SURFACE REGOLITH CAUSED BY A LUNAR LANDER’S EXHAUST PLUME DURING DESCENT AND LANDING. J. G. Mantovani1 and B. T. Vu2, 1NASA Kennedy Space Center, UB-R1, Kennedy Space Center, FL 32899 Email:James.G.Mantovani@nasa.gov, B. T. Vu, 2NASA Kennedy Space Center, UB-R1, Kennedy Space Center, FL 32899 Email:bruce.t.vu@nasa.gov.

Introduction: Previous calculations conducted at NASA Kennedy Space Center have demonstrated how a rocket exhaust plume from an Apollo lunar lander can loft regolith particles and rocks under near vacuum conditions at speeds that could have damaged nearby assets like outposts, mining operations, or historic sites such as the Apollo, Surveyor and other heritage sites on the Moon. Lunar landing simulations [1] have shown that the velocity of the sprayed dust is on the order of 1 to 2 km/s, which is 20 times greater in velocity (or 400 times greater in particle kinetic energy) than that found in typical sand-blasting operations on Earth. Analysis of human-class landers on Mars reveals that deep cratering will occur beneath the exhaust plume, ejecting soil and gravel into high trajectories that will rain down over a blast zone on the order of 1 km radius [2]. In order to develop mitigation strategies and technologies for the Moon (and Mars), it is necessary to predict these effects accurately. Some of the physics is not yet well understood because it is extremely difficult to replicate conditions on Earth in which supersonic jets impinge upon unusual granular soil media under low atmospheric pressure and in a gravity environment that is much lower than on Earth.

It will be essential to the success of future lunar ISRU missions to be able to characterize the chemical effects, as well as the physical effects, on surface regolith caused by a lunar lander’s exhaust plume during descent and landing, particularly in a cold trap area. Chemical contamination of surface and subsurface regolith by the exhaust from a descending lunar lander can have a potentially adverse effect on subsequent ISRU processing of the surrounding regolith.

This presentation will discuss previous work conducted at NASA Kennedy Space Center that studied the potential surface contamination that can be caused by a lunar lander descending into a lunar cold trap area [3]. The results of that study showed how deposition maps of the rocket exhaust products can be constructed based on a lander’s descent profile. Deposition maps make it straightforward to estimate direct exhaust deposition onto the lunar surface, including into lunar cold traps. We will discuss the need to develop instruments for a lunar lander that can provide data to study rocket exhaust plume effects on prepared and unprepared surface regolith during descent and landing, and to detect any lingering effects on the chemical state of surface regolith after landing.

Introduction: Terrestrial Construction Techniques face numerous challenges posed by the different lunar geography and cannot be used. One daunting problem is the production of suitable construction materials. Materials must offer similar strength, durability and other engineering properties to support human habitation as on earth. It is not feasible to transport large amount of construction material from earth to the moon due to large transport costs.

Research: Like many space exploration missions, cost is a determining factor. Transportation alone imposes a cost of $10,000 per kilogram for the entire mission making it simply not profitable or attractive to potential investors. [1] A potential near-instantaneous solution would be to develop an asteroid mining economy developing of a human-commercial market. It is suggested that this scenario will create the economical and technological opportunities not available today. The National Aeronautics and Space Administration (NASA)'s Space Exploration Initiative (SEI) promoted industrial involvement in the research and exploitation of lunar resources in the early 1900's. Although this initiative failed in the end, it prompted NASA to consider engaging industry for financial investments. Future lunar missions must prioritize private investments in this sector in order to meet preliminary program cost. Therefore due to the lack of funding, one feasible solution to reducing mission costs is to use native material such as lunar regolith to produce useful construction material.

It is proposed that a process to devise and extract volatiles from lunar regolith can be used to create construction material on the moon. Currently, space traveling require missions to carry life necessities such as air, food, water and habitable volume and shielding needed to sustain crew trips from Earth to interplanetary destinations. [2] In theory, the focus from any lunar mineral mission will focus on regolith excavation and transportation, water and oxygen production and fuel/energy production. All of these necessities along with construction and site preparation will be taken from the lunar regolith. [3] In-Situ Resource Utilization (ISRU) offers long term sustainability for large human colonization.

The majority of the mineral found on the moon is composed of silicates. Composition of lunar basalts is approximately 50% pyroxenes, 25% plagioclase and 10% olivine by volume. [4] With the chemical composition in mind, the designer must take into account the loads for structure. In basis structural mechanics, a designer must take into account the dead load which is primarily from the weight of the construction material caused by gravity. Internal pressurization and the amount of shielding must also be taken into account as this may increase the dead load. Live loads caused by moving or vibrating objects such as ventilation machinery must be also included in the calculation of overall design. A Factor of Safety (like for terrestrial designs) must be included for accidental impact loads from potential micrometeorites, possible seismic activity, extreme solar maximums and the like. This value needs to be estimated through experimentation. As we cannot test the experiments on the moon, scientists and engineers can only conduct these tests under similar environment which will have a larger factor of error.

Conclusion: Robotic surveys of the lunar surface would be the precursor to the development of in situ resources. Advanced technology directed towards space mineral exploitation, excavation and effective transportation is necessary.

References:
Introduction: For any future construction of lunar bases, terrestrial construction techniques may not be suitable and will face numerous challenges posed by the different lunar geography and distance away from earth. One daunting problem is the production of suitable construction materials, terrestrial construction techniques may not be suitable and will face numerous challenges posed by the different lunar geography and distance away from earth. One daunting problem is the production of suitable construction materials. It is not feasible to transport large amount of construction material from earth to the moon due to large transport costs. Like many space exploration missions, cost is a determining factor. Transportation alone imposes a cost of $10,000 per kilogram for the entire mission making it simply not profitable or attractive to potential investors. [1] Currently, space travelling require missions to carry life necessities such as air, food, water and habitable volume and shielding needed to sustain crew trips from Earth to interplanetary destinations. [2] In theory, the focus from any lunar mineral mission will focus on regolith excavation and transportation, water and oxygen production and fuel/energy production. All of these necessities along with construction and site preparation will be taken from the lunar regolith. [3] In-Situ Resource Utilization (ISRU) offers long term sustainability for large human colonization. The prospect of using lunar lava tubes for housing will also be a subject of our discussion.

Research: Lava tubes are natural conduits formed from lava flows. When the supply source stops, this underground tube is formed as the outer surface of the lava cools and hardens. Unlike lava tubes on Earth which has a maximum diameter of 25 meters, lunar lava tubes can span several hundred of meters wide and tens of kilometers long. [4] This is due to the conditions of basaltic eruptions given the moon’s lower gravity field and little atmosphere and low viscosity flows. Although the size differs, the formational processes appear to be similar. [5] Evidence derived from the study of terrestrial lava tubes along the coast of Hawaii such as the east and southwest rift zones of Kilauea Volcano. Studying the structural stability of the Thurston and Kilauea Caldera Lava Tubes in this region under seismic activities for the past century leads to the conclusion that varied lunar seismic history has minimal effect on lava tubes generated by meteorite impacts and tectonically originated moonquakes. [6] A variety of factors must be considered to determine the structural stability of lunar lava tubes. Generally, visual inspection identifying faults and slumps along lunar rilles will filter out candidates for feasible lava tubes. The ratio of roof thickness to interior tube width determines the feasibility of lunar lava tubes. Under lunar conditions, a ratio of approximately 0.17 is needed for the structure to remain stable. Depending on the arching of the roof, this ratio can decreased to 0.10 to 0.13 allowing for thinner roof depths. [7] Using the Lunar Orbiter and Apollo photographs, the tube lengths can be used and an estimate for the tube depth and roof thickness can be estimated following the crater-geometry Horz formula: \[ t = d \times 0.25 \times 2 \]

Conclusion: Based on the many research conducted by many international institutes, we conclude that the prospect of the usage of lunar lava tubes to serve as housing is a realistic and cost-effective method for future lunar missions. From inspection from lunar satellite images, it is highly likely that lunar lava tubes do exist though there is no concrete way of proving such until the next lunar manned mission. However, it is unknown as to whether or not the 90+ lava tubes identified by Coombs and Hawks have identified 90 lava tube candidates along 20 lunar rilles from the lunar regions of Oceanus Procellarum, Northern Imbrium, Mare Sereitatis and Mare Tranquillitatis.

References:
Introduction: Facilities on the lunar surface will challenge contemporary ideas of structural analysis by structural and civil engineers, as well as designers, constructors and logistics planners. Exposed habitation units will face many issues regarding the extreme lunar temperature cycles and effects of high vacuum. [1] Exposed material and structural fatigue due to extreme lunar temperature cycles and temperature sensitivity differential on continuous structural components must be addressed. Nighttime lows of -110°C (-170°F) would mean designers must look at the potential brittle fractures and stress concentrations within the potential material. [2] A potential partial solution would be to internally pressurize supporting members such as those for buckling, stiffening and bracing to meet safety and reliability requirement. The unpredictable nature of the lunar environment requires minimization of risk to an acceptable level. [3] Loading must take into account the 1/6 gravity of the moon. This means a structure will have six times the weight-bearing capacity (dead weight) on the moon as on the Earth. However, it cannot be assumed that the structure is able to support more load due to this fact. This would only be true if the material is linearly elastic. However, most materials have a non-linear. Current engineering thinking and design is based on the limit-state conditions. Chua et al. (1992) propose a nonlinear hyperbolic stress strain model to better reflect how structure-regolith simulations can be done using the finite element approach. This is exactly the reason explaining the implementation using kg-force (calculations without gravity component). Structural components must display a level of redundancy as in statically indeterminate structures. This implies that loads are redistributed to an equilibrium state when members are to fail. A level of acceptable risk and safety factors needs to be derived.

Research: Inflatables have long been proposed as a feasible and economic method for a permanent lunar base. [4] The inflatable pressurized tensile structure of fibre composites offers radiation shielding under native regolith and little temperature variations. Erectable tetrahedral, hexahedral, octahedral structures have also been proposed and offers many of the same benefits as inflatables. [5] The various geometrically configured space frame elements can be easily expandable and is quick to construct and install. As members of these structures are not natively found, it must be prefabricated and brought to the moon. Currently it is not economically feasible.

Conclusion: This paper presents a summary of pressing issues surrounding the designing, engineering and construction of lunar habitation units. Structural integrity depends on various unpredictable factors present on the moon. Temperature and regolith variations must be factored into the design criterion of the structure. Foundational, Material and Structural mechanics and behaviour are dependent on these variables. Due to different variables within the scope of designing of lunar structures, a method criterion for the consideration of failure modes that differ from terrestrial structures must be created. The challenge during the design phase is the inability to test design prototypes under lunar environment. A realistic testing scenario can be not realistically tested. This in turn does not allow engineers and designers to effectively and accurately evaluate the complete structural life cycle. The distance away from Earth in conjunction with high costs associated with transport of material to the lunar surface suggests the need for the use of native material. This is also known as In-situ Resource Utilization (ISRU). This will be extremely important but future feasibility analysis into this topic must be researched.

References:
ETHICAL CONDUCT IN LUNAR COMMERCIALIZATION. A. A. Mardon¹ and G. Zhou², R. Witiw³,
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Introduction: Ever since the launch of the Sputnik, countries from across the world have continually strive to exploring and one day colonizing of space. [1] With the growing demand on natural resources to fuel intercontinental technological advances, and with reducing terrestrial sources, government and industries are investing in space exploration missions. It is important to develop moral and ethical models for space commercialization, specifically, as it relates to lunar settlements. [2]

Research: The agreement Governing the Activities of States on the Moon and Other Celestial Bodies have been proposed to United Nation members by several member states, however, has not been widely accepted due to its controversial language. Specifically, the provisions requiring spacefaring nations to share the benefits for the “common heritage of mankind” and that no nation should be military bases on the lunar surface creates a conflict between third world countries that argue benefits derived from outer space commerce be equally distributed to all countries and that of free market private sector ideologies. The ethical issues arise when one has to balance between the necessary business profits and the demand for distribution between all nations. One of the challenges with developing an internationally recognized code of conduct is that moral conduct is based on cultural background and context. It will be difficult to create a global framework concerning corporate and commercial behavior as appropriate value system will differ between countries and systems around the world.

Another challenge is related to environmental concern and has always been the question the right to disrupt, and change the character of the lunar surface. The impact of construction, traffic, mining and other human activities related to lunar settlement needs to be analyzed. A balanced approach between the classical environmental concern and corporate and commercial will prove to be a long-term evolutionary process. [4] It is especially difficult to define moral and ethical standards in relation to lunar commercialization as it is based on subjective values that differ between various cultures and societies. One solution is to create a business code of conduct based on objectivity. Through the lens of stewardship, social scientists have proposed three guidelines to ethical conduct to lunar development that resembles a standard business code of conduct: [5] 1. Space Preservation – value space for its own sake regardless of potential benefits that can be derived from it 2. Space conservation – protect and care for the universe’s resources for the sake of all 3. Space stewardship – holding ourselves accountable for managing space resources. By bringing economic development to the moon and beyond for human benefits, the approach that is used to address environmental concerns should be one of the many focus of the business code of conduct.

Conclusion: A legal framework should be further researched so that governments can begin to think about establishing controls on space businesses. The centerpiece of this system must include moral and ethical codes of behaviour for those living and working on celestial bodies in the future. A possible model that exists on earth is the US Federal Lease Royalty Model whereby a certain percentage of royalty to the federal government or Native American tribal government in exchange for rights to continue rights to its operations. The royalty payment will be used by the organization in charge to advance interests for the betterment of all of humanity and to fund initiatives that given equal opportunities to all nations.

A well designed code of ethics facilitates space commerce and creates a common framework for all nations to work within. Nations, corporations and people supporting this initiative in developing this type of fair space economy end up creating a higher purpose for the work pushing the new frontier.

References:
LUNAR RARE EARTH MINERALS FOR COMMERCIALIZATION. A. A. Mardon1 and G. Zhou2, R. Witiw3, 1University of Alberta (116 St. and 85 Ave. Edmonton, Alberta T6G 2R3, CANADA, aamardon@yahoo.ca), 2George Washington University (2121 I St NW, Washington, DC 20052, USA, gzhou@gwu.edu), 3Antarctic Institute of Canada (103 11919 82 ST NW, Edmonton AB, CANADA, riley.w@live.ca)

Introduction: Since the formation of the Moon, collisions of meteorites and comets have impacted the lunar surface creating a great variety of impact craters. Unlike the Earth which has been molded by natural forces through its lifetime, the Moon through its airless and waterless environment has left the lunar surface largely untouched and containing clues of the historical events of the early solar system [1]. With depleting natural resources on Earth, some companies and entrepreneurs have been drawn by the Moon’s rough surfaces and investigating feasibility of procuring Rare Earth Elements (REE) from the Moon for terrestrial consumption. One of the many current challenges is that it is currently not economical to lift massive quantities of oxygen, water, structural materials and other vital elements between Earth and the Moon [2]. While technological advancement in this arena continue to develop so that it may one day be more cost-effective for this future business venture, the first of many steps to bringing these ideas to commercialization include producing a well-founded business case to support whether there are enough amounts of REE on the Moon.

Research: Rare earth elements are ultra-rare and previous deposits that can be used in a variety of applications most of which are used on electronics for consumers and defense systems alike. Recent estimates put the global reserves at 140 million tones with the abundance of its deposits located in China (55M) and India (35M) [3].

Based on lunar meteorite samples, lunar samples show different relative concentrations of REE compared to compositions found in the Earth’s crust [4]. The graph below for feldspathic lunar meteorites show the varying degrees of concentrations for each element as an example.

![Graph of REE concentrations](http://meteorites.wustl.edu/lunar/chemclass/ree.htm)

Most other lunar samples from Apollo, and Luna missions show REE-bearing minerals only as trace phases to include monazite, yttrotitanite and tranquillityite. Given the current information to date, the conclusion shows that there is relatively low REE abundance compared to terrestrial amounts [5].

Conclusion: Beyond the commercial aspect of lunar mining, the seemingly untapped and mineral-rich lunar quarry may also be of strategic and national security importance for the United States and her western allies. Although current studies show that there is not enough REE on the Moon, there may be other minerals that may justify a business case to continue with this investigation on potential lunar mining in the future. With China’s growing clout in securing resources around the world and recently blocking exports of rare earth metals from within its boundaries, there may well be another pressing reason for governmental involvement and international collaboration amongst allies to supplement already existing commercial investment for strengthening efforts in lunar geology assessments in relation to lunar mining and full-scale commercialization.

References:
SULPHUR-BASED REINFORCED CONCRETE UNDER LUNAR CONDITIONS A. A. Mardon¹ and G. Zhou², R. Witwi³, ¹University of Alberta (116 St. and 85 Ave. Edmonton, Alberta T6G 2R3, CANADA, aamardon@yahoo.ca), ²George Washington University (2121 I St NW, Washington, DC 20052, USA, gzhou@gwu.edu), ³Antarctic Institute of Canada (103 11919 82 ST NW, Edmonton AB, CANADA, riley.w@live.ca)

Introduction: Composition of lunar lava tube regolith is also a variable determinant of structural stability. After identifying intact lava tubes, the concept of “lunar concrete” is introduced to increase loading capacity.

Research: Unlike under terrestrial environments, hydraulic concrete comprising of cement, granular and water may not be suitable under lunar conditions. The primary reason is that the moon does not contain any provable amounts of water. Transportation of this liquid from earth is also not economically feasible given the technology to date.

Composition of lunar lava tube regolith is also a variable determinant of structural stability. After identifying intact lava tubes, the concept of “lunar concrete” is introduced to increase loading capacity. As well, it may also be used for radiation shielding and temperature variance protection. Cast regolith would be very similar to terrestrial cast basalt where the regolith is melted and let to cool to form a crystalline structure. The compressive and tensile building components are strengthened as a result.

Sulphur-based concrete is proposed to replace hydraulic based concrete for lunar construction. Advantages of sulphur-based lunar concrete are its strength, durability and excellent shielding properties. In terms of economics, the construction and transport costs are both reduced using the concept of In-Situ Resource Utilization (ISRU). Sulphur-based concrete samples were created to study the feasibility of using lunar regolith and binders. The most important factor in using sulphur concrete compared to terrestrial hydraulic concrete is that it does not need water to gain strength through chemical reaction. The test shows that this type of concrete can gain full strength in a relatively short period of time and requires less heat to manufacture. [1] Because concrete of any sort is a rather brittle substance, Dr. Omar introduced metal fibres in the matrix to increase tensile strength and reduce brittleness. The finding concludes that the 25.4mm fiberglass fibres of 0.25% and 0.50% weight reduced compressive strength by 27% and tensile strength by 20%. [2] The majority of the mineral found on the moon is composed of silicates. Composition of lunar basalts is approximately 50% pyroxenes, 25% plagioclase and 10% olivine by volume. [3] With the chemical composition in mind, the designer must take into account the loads for structure. In basic structural mechanics, a designer must take into account the dead load which is primarily from the weight of the construction material caused by gravity. Internal pressurization and the amount of shielding must also be taken into account as this may increase the dead load. Live loads caused by moving or vibrating objects such as ventilation machinery must be also included in the calculation of overall design. A Factor of Safety (like in terrestrial design building codes) must be included for accidental impact loads from potential micrometeorites, possible seismic activity, extreme solar maximums and the like. This value needs to be estimated through experimentation. As we cannot test the experiments on the moon, scientists and engineers can only conduct these tests under similar environment which will have a larger factor of error. Recent experimentation by Toutanji et. al. explored replacing the binding mix of concrete with sulphur and JSC-1 lunar simulant. The lunar simulant was produced by Johnson Space Centre as an aggregate addition in lieu of the proposed lunar regolith. The study concludes the Sulphur-based concrete is feasible under lab environment simulating lunar conditions [4].

Conclusion: Reinforcement of lava tubes by sulphur-based concrete using lunar regolith is a feasible solution. Compared to hydraulic cement concrete used on earth, it pose similar strength and durability as indicated in experiments. Due to the unknown nature of the lunar surface, these properties may change and therefore it is difficult to evaluate the performance of such a material on the lunar surface. Despite the construction material being potentially feasible, the entire application process of Sulphur-based concrete will need to be explored. The process of forming, steel reinforcement installation, pour and curing under lunar environments has not been explored and will need to be looked at in a greater detail.

References:
THE USE OF THERMAL MASS IN A LUNAR SURFACE STRUCTURE

The amount of thermal mass contained within a building material is determined by its heat storage capacity. Any high-mass, homogeneous, granular or cementitious material has both resistive and capacitive insulating properties. Solar radiation incident upon the exterior surface of the building envelope is stored within the most massive building components and later emitted as long-wave thermal radiation to the interior space. A thermal storage cycle is generated when the ambient diurnal temperature gradient in combination with optimum thermal mass creates a time-lag effect. If designed properly, a thermal storage mass will delay solar penetration until the evening under cooler conditions when it is needed. Applying the thermal mass / heat storage mechanism to a layer of the lunar regolith would simultaneously provide a lunar surface structure with thermal insulation and natural supplemental heat energy (reducing the energy requirements met by mechanical equipment) as well as the added utility of micrometeorite and radiation protection.

Previous simulation studies that were done by the author to analyze the effectiveness of thermal mass in differing climatic conditions on Earth found that the heat storage cycle is most productive in the presence of a large diurnal temperature gradient. An extremely large temperature gradient exists in the equatorial region of the moon, making it particularly suited to the use of thermal mass. For surface structures located near the lunar equator, simulation data indicates a substantial reduction in thermal energy requirements when thermal mass is integrated into the construction assembly. Preliminary results will show that natural positive heat flows (heat gain) will significantly increase temperatures in an unconditioned interior space on the lunar surface during the lunar night. In addition to providing supplemental heat energy and radiation protection, the regolith acts as resistive insulation against the extremely high temperatures occurring during daylight on the lunar surface. This will completely eliminate the need for cooling / refrigeration within the habitat’s living space. A slight variation in the thickness of the regolith layer can negate the effects of all three strategies. The energy gains realized from the use of a thermal mass system continue indefinitely, for as long as the structure exists, and the system itself requires no maintenance, monitoring or fuel.
HIGH FIDELITY MODEL OF LUNAR VOLATILE EXTRACTION INDICATES CHALLENGES AND SOLUTIONS TO ECONOMIC RESOURCE RECOVERY. P. T. Metzger\textsuperscript{1} Affiliation (include full mailing address and e-mail address if desired) for first author, \textsuperscript{2}Affiliation for second author (full mailing address and e-mail address).

**Introduction:** Lunar regolith is a bad thermal conductor. Mixed chemistry ice changes its properties. As vapors diffuse the pore pressure increases the thermal conductivity by orders of magnitude. Physics-based modeling is needed to enable design of lunar volatile mining technologies.

**Modeling Framework:** A model is developed using Crank-Nicholson formalism extended from 1D to 2D axisymmetric. It can be extended to 3D cylindrical or cartesian. Gas diffusion and heat transfer have vastly different characteristic transport times so multiple, adaptive timesteps are incorporated for speed.

**Thermal Conductivity:** Realistic chemistry and abundance of lunar ices from LCROSS data modify the thermal conductivity and heat capacity. Guided by first principles, a thermal conductivity equation is developed for lunar regolith that is a function of both porosity and temperature. The data of [1] in Fig. 1 fit the model within expected experimental accuracy. For gas pore pressure, analysis reconciles extant data sets (Fig. 2) and finds an empirical model.

![Figure 1](image1.png)

**Figure 1.** Data from [1] with crushed basalt as lunar simulant at six different porosities.

![Figure 2](image2.png)

**Figure 2.** Top curve from [2]. Color curves from [3]. Bottom from [1]. All at T~300K. Dashes are the model. [3] does not fit the model apparently due to spherical particle shapes.

**Predictions:** The model was partially validated with LRO Diviner data of regolith cooling during the lunar night. It also replicates data from asteroid Bennu rotating in sunlight. Fig. 3 is a series of snapshots from a simulation of a coring devices screwed into the regolith heating the enclosed material.

Simulations of a heated tent over the lunar regolith predict days to target sublimation rate at each depth. The temperature gradient tends drive volatiles deeper into the regolith away from the capture system, so modeling is needed to design ways to avert this.

![Figure 3](image3.png)

**Figure 3.** Cross section of coring device embedded in regolith, heating the interior and liberating volatiles. Top panel: temperature field. Bottom: pore pressure.

![Figure 4](image4.png)

**Figure 4.** Temperature under heated tent on lunar surface after day 1 (black), 5 (blue) and 10 (red). Dots: depths where sublimation rate is achieved.

MITIGATING LANDER PLUME EFFECTS WITH SPACE RESOURCES. P. T. Metzger¹ and D. T. Britt²,
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Introduction: Lunar lander engine exhaust blows soil, rocks, and dust at high velocity and will damage surrounding hardware such as lunar outposts, mining operations, or historic sites unless the ejecta are properly mitigated. The Center for Lunar and Asteroid Surface Science (CLASS) has established the
CLASS Planetary Landing Team bringing together world-leading expertise in analyzing, modeling, and mitigating the problems of lander plume effects, along with representatives from the major commercial lander companies. Twenty years of research have developed a consistent picture of the physics of rocket exhaust blowing lunar soil, but significant gaps exist. No currently-available modeling method can fully predict the effects. However, the basics are understood well enough to begin designing countermeasures. To be low-mass, they must use lunar resources.

Understanding and Modeling the Physics: Our prior work characterized the different regimes of transport that can occur under various plume and planetary environment conditions [1-8]. While rocket exhaust can deeply crater Martian regolith, the lunar effects are largely restricted to surface scouring a few centimeters of looser material. Lunar regolith is highly compacted deeper than a few centimeters and the lack of an atmosphere to collimate the plume prevents abrupt pressure gradients from the surface that would otherwise cause the soil to deform into a crater. However, a possible exception may occur in the permanently shadowed regions where soil may be looser (as suggested by several lines of evidence) or with a larger lander on a soft crater rim.

Our team’s prior work developed a model of lunar landing ejecta flux based on the available empirical data which predicts quantities of each particle size, their velocities, and impact angles for each location on the Moon, scaled by lander thrust-trajectory curve and distance to landing site [9,10]. We quantified several types of damage to neighboring hardware via analysis of the Surveyor III spacecraft that was sandblasted by the Apollo 12 landing [11] and by performing hypervelocity impacts of appropriate particle sizes and velocities onto additional materials. Based on this, Metzger wrote the relevant sections of NASA’s document to protect the historic sites on the Moon. Recently, members of the CLASS team used Apollo data to derive a more accurate equation of soil ejection from the lander thrust-trajectory curve [12].

Mitigating via ISRU: Our results show plume ejecta are impossible to simply block with a berm or fence because particles colliding in flight scatter over the barrier. Also, larger particles like rocks loft over the barrier and arc down into the other side, and the berms themselves scatter the particles in lunar vacuum. Berms can reduce ejecta damage, but full mitigation requires construction of a landing pad. CLASS team members have prototyped and studied technologies including sintering lunar regolith with microwaves, sunlight, and/or infrared radiation, application of polymers to regolith, the use of gravel and pavers, lunar concrete, and more. They have tested robotics for grading and compacting lunar landing zones. Our team members also tested 3D printing of regolith that can construct walls, and non-ISRU solutions such as deployment of inflatable blast barriers. Each method has drawbacks, so downselection to a set of complementary technologies is required.

Next Steps: We are pursuing three approaches to fully address the plume challenges. First, we are continuing research into the physics to close the gaps, leading to more predictive computer models. These will set better requirements for landing operations and landing pad construction. Second, we are testing and assessing each mitigation technology including sintering lunar regolith and other methods to create competent surfaces, robotics for bulldozing and berm building, and the use of gravel or pavers. This will lead to a recommended downselection. Third, we are organizing a series of robotics competitions for landing pad construction technologies in conjunction with Machine Learning companies to further advance the necessary robotic capabilities.

**ESA activities as support to ISRU technology development.** A. Meurisse¹ and J. Carpenter², ¹Research Fellow, European Space Agency - ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, Netherlands, alexandre.meurisse@esa.int, ²Scientist, European Space Agency - ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, Netherlands).

**Introduction:** Previous ad hoc funded projects [1-2], and PROSPECT activities [3] have raised an interest in lunar resources in Europe. Following the successful July 2018 ISRU workshop held at the European Space Research and Technology Centre (ESTEC), Noordwijk, The Netherlands, the European Space Agency (ESA) is now developing a space resources strategy, focusing on short, medium and long term rationales and addressing whether space resources can enable sustainable space exploration, having the Moon as a primary target.

In this endeavor, ESA has triggered a number of activities to develop ISRU technologies and processes: two terrestrial ISRU end-to-end demonstrators producing water and the phase A of an ISRU demonstrator mission.

**Terrestrial ISRU demonstrators:** By the end of 2019, ESA will own two end-to-end terrestrial demonstrators producing oxygen from different lunar regolith simulants. One demonstrator will reduce the material by hydrogen reduction when the second one will carry out a carbothermal reduction of the material. Several lunar simulants will be tested in order to observe the impact of mineral variations on the two processes. Both processes could handle batches of 1 kg of soil and will be further used for ISRU research in ESTEC premises.

**ISRU demonstrator mission:** ESA is also preparing an ISRU demonstration mission. The objective of the mission is to characterize the feedstock material at the landing site and test critical ISRU technologies to pave the way towards robust end-to-end lunar ISRU processes. This could be done as a single mission or as a campaign through several missions, having first feedstock characterization payloads, then technology maturation payloads and finally, end-to-end demonstrator payloads. ESA expects to make use of soon available commercial landers to bring the payloads onto the lunar surface.

The focus of the mission is going towards building water/oxygen production capability from lunar soil. The mission phase A which started in November 2018 is a feasibility study and aims at identifying which key technology could be ready before the launch date, expected in 2023. As for smaller secondary ISRU payloads, launch opportunities could be created as early as 2020.

**References:**
ISRU: An approach to change and knowledge gaps to fill for viable processes in space. A. Meurisse\(^1\) and J. Carpenter\(^2\), \(^1\)Research Fellow, European Space Agency - ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, Netherlands, alexandre.meurisse@esa.int, \(^2\)Scientist, European Space Agency - ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, Netherlands.

**Introduction:** In-Situ Resource Utilization (ISRU) is once again seen as a way to facilitate the exploration of the solar system, particularly at the Moon and Mars. For reducing the cost, limiting the up-launch mass from Earth or creating a more autonomous and safe environment for the astronauts and other explorers, the versatility of ISRU appears as a strong asset to any long crewed exploration mission. In order to play their roles, the ISRU processes have to survive the harsh space environment which includes dust, radiations and cyclic extreme hot and cold temperatures. ISRU will however not take part in a mission plan before the reliability of the processes over time with a multi-compound feedstock material – not thoroughly characterized – has been significantly proven. Works towards this goal, have started around 1963, over the first *Working Group on Extraterrestrial Resources* [1], and yet, there is still a long way to go before using technologies utilizing local materials in space missions.

This work aims at stepping back to analyze what went wrong, what could be done better in the future in the development of ISRU technologies and processes, and where should be the particular research focus for the next decade.

**A Change of Focus:** The ISRU development strategy has so far been engineering-driven. Designing and building terrestrial demonstrators for oxygen production [2] and construction [3] are the focus of the funded studies as they provide visibility and proofs of concept of the different ISRU processes. The Technology Readiness Level (TRL) reaches 3 or 4 and then stops. The step to TRL 5 involves the need of a *relevant environment* according to ESA and NASA definitions, meaning at least the use of relevant analogue material and vacuum. These two requirements have never been met so far: the simulants material never seems to be representative enough of the extraterrestrial material and the vacuum is only applied at lab-scale, with a pressure usually down to \(10^{-5}\) mbar when the lunar vacuum is about \(10^{-12}\) mbar. This recurring issue for all kinds of ISRU processes may be an indication that a rationale exists in changing the strategy used so far in ISRU research.

One new option is to have materials science-driven ISRU research, targeting a deeper understanding of the existing processes at the mineral level. An extensive fundamental knowledge of the physicochemical properties of the different extraterrestrial minerals and of the thermodynamic involved in ISRU processes may be more beneficial in the long run that the trial-and-error approach used heretofore with various simulants.

Another option would be to concede that it is not feasible to reproduce the lunar or Martian conditions for a reasonable cost and that ISRU technologies should be tested – as the acronym implies – *in-situ*. Demonstration missions could fill key knowledge gaps in short term for lunar ISRU research, as is being developed commercial landers which could offer missions opportunities.

**End-to-end consideration:** ISRU could only be taken into account for a mission when the end-to-end processes will be fully covered. Most of past and current ISRU researches omit the potential presence of compounds like Sulfur in the feedstock which could react with the process gas (e.g. hydrogen), the binder or the equipment. After a reduction process, the produced water is usually not characterized and information regarding its use for life support or for an electrolysis step remains unknown. Radiation impact on the end-product has also so far been poorly considered. Filling these pre- and post-process gaps could be done now, on Earth, and would support the overall use of local resources for a sustainable human exploration.

**References:**


Introduction: Draper (Cambridge, MA), the company that developed the guidance, navigation, and control algorithms that made NASA’s Apollo landing possible, is returning to the moon. Draper was selected as a provider for NASA’s Commercial Lunar Payload Services.

Enabling Lunar ISRU: NASA’s Lunar Surface Instrument and Technology Payloads opportunity will be used to select lunar experiments to address strategic knowledge gaps for technologies needed to support human lunar missions and scientific exploration. Draper’s NASA CLPS offering is ideal for enabling lunar ISRU missions to identify, characterize, extract, and process lunar resources. Technologies onboard the lander open new landing site opportunities and will enable direct deployment to lunar resources to reduce traverse time for rovers and locating lander-fixed instruments closer to scientific points of interest.

Vision Based Navigation: Advanced vision-based navigation and hazard avoidance systems enable Draper to deliver CLPS payloads with exceptional accuracy to areas that are too dangerous for blind landers to attempt. This system looks for hazards that become visible during descent and updates guidance as needed. Feature detection algorithms developed from decades of Draper expertise in vision systems are used to enhance the navigation solution to further improve landing accuracy. This presentation will discuss these methods and explain they reduce time to areas of interest for ISRU and science objectives.

Additional Information: If you have questions about our payload capability related to NASA CLPS and NASA LSITP, please contact Draper at clps@draper.com.

Acknowledgements: Draper would like to acknowledge our partners for NASA CLPS: ispace (lunar lander design), General Atomics Electromagnetic Systems (manufacturing, assembly, integration and testing), and Spaceflight Industries Inc. (launch services.)
LUNAR VOLATILE-RICH SAMPLE STORAGE AND HANDLING FOR CURATION AND ISRU. J. L. Mitchell¹, E. K. Lewis², K. R. Fisher¹, R. A. Zeigler¹, and M. D. Fries¹, ¹NASA Johnson Space Center, 2101 NASA Pkwy, Houston, TX (Julie.L.Mitchell@nasa.gov); ²Texas State University/Jacobs Engineering.

Introduction: Water and other volatiles serve as resources for humans on the lunar surface. The poles are particular targets because they harbor volatile reservoirs. The Johnson Space Center (JSC) is focused on enabling human missions and preserving volatile-rich materials for Earth return and curation. This abstract summarizes Internal Research and Development (IRAD) funding that has been used in FY19 to accelerate development for future lunar polar missions. This work is split into two complementary and parallel efforts: lunar polar simulant development and lunar environment technology development.

Lunar Polar Simulant Development: A lunar polar simulant is in development that includes both a high-fidelity silicate component and a moderate-fidelity volatile component. The silicate component includes a highlands-type lunar simulant (either USGS-LHT or OB-1) that replicates the anorthosite composition and grain-size distribution of particles observed in returned lunar samples. The volatile component replicates the dominant compounds observed by the LCROSS mission [1], and will be expanded to include volatiles with lower condensation temperatures once gas handling capabilities are fully operational. This simulant is being used for cold (-20°C, -80°C) and cryogenic (-196°C, <-220°C) storage testing to ascertain the ideal storage conditions a) during transport to Earth from the lunar surface, and b) during curation operations after Earth return.

Lunar Environment Technology Development: Development is underway on a new planetary surface environment chamber within the Astromaterials Research and Exploration Science (ARES) group at JSC. The vacuum chamber will mimic as closely as possible the lunar exosphere surface environment. It will be capable of operating at ultra-high vacuum (UHV) (<10⁻⁹ Torr) and cryogenic temperature ranges [e.g., 2]. A residual gas analyzer and, later, a gas chromatograph mass spectrometer will be integrated to monitor outgassing of materials. The chamber design consists of an inner volume of 35L with eight Conflat ports of varying sizes at 45 degrees to each other. Sample cooling using either liquid helium or liquid nitrogen are integrated in the chamber design. In progress are three temperature zones which aim to allow for controlled temperature ramping of samples and monitoring of lunar simulant outgassing under UHV handling conditions and various pressure and vacuum regimes.

The capability to monitor a volatile-rich lunar simulant under permanently shadowed or dosed solar illumination conditions within a lunar exosphere environment will provide valuable information for the curation and ISRU communities. The chamber will also be able to thermally cycle samples to mimic the temperatures that may be experienced during sample return or ISRU activities. Alteration of the samples will be observable and using this information we will be able to test curation and ISRU techniques. Knowledge of the chemical changes of the sample under various thermal/pressure regimes is paramount for the design of future polar lunar missions. The chamber check-out is on schedule for completion in mid-2019 with preliminary testing following.

Conclusion: The utility of a lunar polar simulant extends to curation sample handling and storage, and to testing both the functionality and efficiency of ISRU hardware. The lunar environment chamber will allow storage testing of the lunar polar simulant under realistic (lunar-like) collection and processing conditions, maximizing the fidelity of experiments studying sample preservation, volatile extraction capabilities, and general sample handling. This work is laying the foundation for future lunar polar sampling and ISRU efforts by providing realistic materials and conditions upon which future surface operations planning and design can be based.

Fig. 1. Lunar cryogenic environmental chamber at JSC.

RESULTS AND LESSONS LEARNED FROM TESTING OF THE PLANETARY VOLATILES EXTRACTOR (PVEx) AND RELATED ISRU CONCEPTS. P. D. Morrison\(^1\), K. A. Zacny\(^2\), and V. R. Vendiola\(^2\), A. Paz\(^2\) \(^1\)Honeybee Robotics, 398 W. Washington Ave, Suite 200, Pasadena, CA 91103, pdmorrison@honeybeerobotics.com, \(^2\)NASA Johnson Space Center.

Introduction: Honeybee Robotics has a long history of developing prototype and flight surface-preparation, sampling, and sample-processing systems for Martian, Lunar, and other space applications. More recently, Honeybee Robotics has explored a number of In Situ Resource Utilization (ISRU) concepts including the Mobile In-Situ Water Extractor (MISWE) [1], the World Is Not Enough (WINE) water-extraction system [2], and various low-TRL designs [3].

Among these ISRU concepts, the most mature is a system referred to as the Planetary Volatiles Extractor (PVEx) [4].

Planetary Volatiles Extractor (PVEx) consists of a coring auger with an internal heated sleeve that sublimes ice or bound water within a regolith core, and a cold trap with associated plumbing that condenses the released water vapor for capture (Figure 1). The nominal dimensions of the coring auger is 5 cm in diameter and 50 cm long. As such, every time the PVEx system is deployed, it captures a volume of material approximately 1000 cc.

However, PVEx can be easily scaled up depending on the volumes of the material required. As such, it can serve as initial reconnaissance tool and a production system. For example PVEx 20 cm in diameter and 1 m long, can capture 3 kg water/hour (assuming 5 wt% and 2 g/cc regolith density). A Curiosity size rover with four PVEx systems will therefore capture 12 kg water/hour or 50 MT water/year (assuming 50% duty cycle: 50% water extraction and 50% driving, drilling).

The main attribute of the PVEx approach is that it can perform well in dry and ice cemented regolith. If the subsurface strength is unknown, this type of drilling based ISRU system is one of the few that could be used without worry that the system will not work. Based on our tests, even a small fraction of water (1%) is sufficient to sinter soil grains together forming a competent and strong material that can not be broken up by a scoop [5].

The PVEx system has been tested in limestone rock and solid ice under ambient and cold conditions, and in ice-bearing regolith simulant under vacuum conditions. During all tests, Weight on Bit was kept significantly less than 100 N. The test data is shown in Table 1. It can be seen that PVEx can reach a depth of 50 cm in 6-10 minutes with ~100 Watt of power. It has been therefor shown to be mechanically robust and also capable of efficiently collecting near-surface and subsurface water in various forms. PVEx consistently collected more than 80% of the water within an ice-bearing sample with energy input predominantly going toward ice sublimation (Table 2).

![Figure 1. Prototype PVEx and drilling system during setup for vacuum chamber testing.](image)

<table>
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<th>Material</th>
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<tr>
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<td>120</td>
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<tr>
<td>Power W</td>
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<table>
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<th>Data Points</th>
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<tbody>
<tr>
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<tr>
<td>Min</td>
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<tr>
<td>Max</td>
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<tr>
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<tr>
<td>StDev</td>
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<td>Water Recovery [%]</td>
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<td>Avg</td>
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Acknowledgments: This work has been supported by NASA Small Business Innovation Research (SBIR).

Mass Spectrometers for In-Situ Resource Utilisation. A. D. Morse¹, F. Abernethy¹, S. J. Barber¹, S. Lim¹, H. Sargeant¹, S. Sheridan¹, I. P. Wright¹, ¹Affiliation School of Physical Sciences, The Open University, Walton Hall, Milton Keynes MK7 6AA, UK. Email: andrew.morse@open.ac.uk

Introduction: The Open University has a heritage in developing small mass spectrometers for planetary lander payloads. The first was a 6 cm radius magnetic sector instrument for light element isotopic analysis (H, C, N, and O), part of the Gas Analysis Package (GAP) on the Beagle 2 Mars lander [1]. The second was the Ptolemy ion trap mass spectrometer (ITMS) on the Philae lander which successfully operated and returned results during the comet landing in November 2014 [2]. The Ptolemy ion trap unit fits within a 10 x 10 x 10 cm cube, including RF, detector and ion source electronics and is capable of a mass range from 10 to 150 amu at unit resolution. Development is continuing for purposes ranging from lander instruments (ProSPA and LUVMI), to rugged deployable probes (penetrators) and for process monitoring within ISRU plant. Many of the planned developments are aimed at the various stages of lunar ISRU, from resource prospecting to demonstration and optimisation of extraction processes.

ProSPA: is a versatile laboratory for in situ analysis of samples drilled from high-latitude regions of the Moon in the Roscosmos Luna-27 mission scheduled for 2023 [3]. ProSPA will receive regolith samples of \( \sim 50 \) mg and seal these in miniaturised ovens, to be imaged and then subjected to thermochemical processing for extraction of volatiles. The released gases are identified and quantified in an ITMS derived from Ptolemy, and isotopically characterised in a development of the GAP isotope ratio mass spectrometer. ProSPA will also perform an ISRU experiment aimed at extracting water from regolith through reduction of ilmenite by hydrogen, in which the ITMS will identify and quantify any water produced in the process.

LuVMI: (Lunar Volatile Mobile Instrumentation) Is a light weight rover designed to explore polar regions of the Moon and drive into a permanently shadowed region. It will insert an analysis package into the soil. The soil will be heated to release volatiles into a Ptolemy type ion trap mass spectrometer to determine the amount of trapped water.

Penetrators: The small compact size of an ion trap mass spectrometer opens up opportunities for a remote deployable instrument [4]. A more robust design of the Ptolemy ion trap has been developed and field tested on rocket sledge at Pendine. Following impact testing at 300 m s\(^{-1}\) the mass spectrometer was extracted from the penetrator and successfully operated. In addition to deployment by high speed penetrators, such a low mass instrument is suitable for surface launch into inaccessible or difficult to access locations such as permanently shadowed regions or lava tube skylights.

ISRU Process monitoring: The small size and versatile nature of the ion trap mass spectrometer make it ideal for monitoring the gas composition during ISRU production of oxygen by hydrogen reduction of ilmenite [5] or carbothermal reactions. A vacuum microwave facility has just been commissioned at The Open University to investigate the use of microwaves to sinter lunar regolith for 3D printing habitats. The microwave facility includes a mass spectrometer to quantify the release of volatiles during heating. Adding hydrogen during the heating will also investigate the potential of oxygen production by reduction of ilmenite.

Introduction: Outer space contains a vast amount of resources that offer virtually unlimited wealth to the humans that can access and use them for commercial purposes. One of the key technologies for harvesting these resources is robotic mining of regolith, minerals, ices and metals. The harsh environment and vast distances create challenges that are handled best by robotic machines working in collaboration with human explorers. Humans will benefit from the resources that will be mined by robots. They will visit outposts and mining camps as required for exploration, commerce and scientific research, but a continuous presence is most likely to be provided by robotic mining machines that are remotely controlled by humans. These robots often have the same functions that are required for construction tasks. Excavation, hauling and dumping are all examples of common capabilities required.

There have been a variety of extra-terrestrial robotic mining concepts proposed over the last 40 years and this talk will summarize and review concepts in the public domain (government, industry and academia) to serve as an informational resource for future mining robot developers and operators. The challenges associated with these concepts will be discussed and feasibility will be assessed. Future needs associated with commercial efforts will also be investigated.

In-Situ Resource Utilization: When considering all aspects of ISRU, there are 5 main areas that are relevant to human lunar and Mars exploration:

1. Resource characterization and mapping for planning and science
2. In-situ production of mission critical consumables and propellants for crew, power, and transportation
3. Civil engineering and construction for hardware and crew protection and infrastructure growth
4. In-situ energy production and storage
5. In-situ manufacturing, repair, and reuse

Robotic Mining & Construction: With automation technology robustness and capabilities progressing rapidly, terrestrial mining is trending towards more automation which results in removing humans from dangerous areas as well as increasing production. This will result in:

- Increased safety and improved working conditions for personnel
- Improved utilization by allowing continuous operation during shift changes
- Improved productivity through real-time monitoring and control of production loading and hauling processes
- Improved draw control through accurate execution of the production plan and collection of production data
- Lower maintenance costs through smooth operation of equipment and reduced damage
- Remote tele-operation of equipment in extreme environments
- Deeper mining operations with automated equipment
- Lower operation costs through reduced operating labor
- Reduced transportation and logistics costs for personnel at remote locations
- Control of multiple machines by one tele-operator human supervisor or fully autonomous operations.

With the rapid acceleration of information technology and micro-processor capability, the technologies driving robotic control of mining equipment in terrestrial markets will be available for a “spin-in” to the space industry at relatively low cost. The terrestrial robotic mining technologies will have to be customized and adapted for use in space environments, but many parts, algorithms and sub-systems can be used for leveraging an extra-terrestrial mining industry. Examples include vision processing systems, LIDAR, sensors, harmonic drives, long life bearings, advanced mobility, micro-processors, end-effectors, human-machine interfaces and methodologies for operations.
GEOTECHNICAL PROPERTIES OF BP-1 LUNAR REGOLITH SIMULANT. R.P. Mueller and J. G. Mantovani, 1Swamp Works, Exploration & Research Technologies, Mail Code UB-R1-A, NASA Kennedy Space Center, FL 32899; PH (321) 867-2599; email: rob.muller@nasa.gov; 2Swamp Works, Mail Code UB-R1-A, NASA Kennedy Space Center, FL 32899; PH (321) 321.867.1870; email: james.g.mantovani@nasa.gov

Introduction: Understanding the mechanical behavior of lunar regolith is of great importance for future missions to the Moon and other similar extraterrestrial environments. However, due to the scarcity of lunar regolith a number of simulants have been developed to facilitate experimental testing. This paper presents the geotechnical properties of an inexpensive lunar regolith simulant named Black Point 1 (BP-1). An experimental program including particle-size distribution, microscopy observations using scanning electron microscope (SEM) images, density measurements, compressibility, and shear strength was performed. Additionally, BP-1 was compared with regolith recovered from lunar missions and a number of its simulants. The physical properties of BP-1 were found to be similar to other existing simulants and to the natural lunar regolith.

One of the main future challenges for the National Aeronautics and Space Administration (NASA) is to create infrastructure for possible settlement on the Moon. Understanding soil properties of lunar regolith is essential for design and construction of prospective facilities such as landing pads and base stations. Lunar regolith is defined as the layer of unconsolidated rocks, pebbles, gravel, and dusty soil placed on primitive lunar bedrock. Regolith is created by repeated meteoroid impacts, which generates a loose, unconsolidated, and very fine crust that is believed to be several meters thick. The study of lunar regolith properties is also essential for proper design of lunar vehicles and excavators.

Black Point Lunar Simulant (BP-1).

BP-1 is made from Black Point basalt flow and silt-sized washing paste from a rock quarry in San Francisco Volcanic Field, located in northern Arizona. BP-1 is available in abundance, which permits use of approximately 52 m³ during the NASA Robotic Mining Competition (RMC) annual student competition. BP-1 is alkaline, and a chemical analysis indicated a composition of silicon dioxide (SiO₂) (47%), dialuminum dioxide (Al₂O₂) (17%), calcium oxide (CaO) (9.2%), and approximately 6% of ferric oxide (Fe₂O₃), iron oxide (FeO), and magnesium oxide (MgO). Previous particle distribution tests have indicated that physical properties of BP-1 are similar to those of JSC-1A and lunar regolith. A comprehensive experimental study detailing the geotechnical properties of BP-1 has not been performed by Eduardo Suescun-Florez et al. as a part of his doctoral work at New York University. This talk will present test results and comparison of BP-1 performance to other existing lunar regolith simulants including MLS-1, JSC-1, JSC-1A, and GRC-3.

Geotechnical Properties of BP-1 Lunar Regolith Simulant. A series of laboratory experiments were carried out to find out the geotechnical properties of BP-1 and to compare them with the properties of lunar regolith and its available simulants. Most test procedures followed their respective ASTM standards; however, some were modified to accommodate the special nature of BP-1. Most experiments were conducted several times to guarantee consistency of results.

Physical and mechanical characterization tests were carried out to study the geotechnical behavior of the Black Point lunar regolith simulant (BP-1) and compare it with the behavior of lunar regolith and other available simulants. Granular size distribution indicates that BP-1 falls within the _1 standard deviation range of the lunar regolith particle distribution. BP-1 is classified as silty sand (SM) and was found to have no segregation of particles during transportation. The average specific gravity was found to be 2.81, which is slightly lower than that of JSC-1A and much lower than those of MLS-1, JSC simulants, and lunar regolith.

The maximum and minimum void ratios are 0.965 and 0.49, respectively. These values appear within the normal range of void ratio values corresponding to other lunar regolith simulants. One dimensional consolidation analysis has shown that compressibility and swelling index of BP-1 soil are lower than those from natural occurring soils but similar to other simulants such as JSC-1A and GRC-3. Shear strength properties were presented within the context of Mohr-Coulomb failure criteria. The peak angle of internal friction of BP-1 is high and increases with density, with negligible cohesion. The measured peak friction angle is in the range of 39 to 51° depending on the confining pressure and the sample relative density. Also, as expected, dilatation decreases as confining pressure increases and as density decreases.

In summary, available geotechnical properties of BP-1 are consistent with those of lunar regolith and other regolith simulants.

Reference:
Introduction:
VISION
Our vision is to be the premier government research and technology laboratory for development of spaceport systems on Earth or at any space destination.

MISSION
Our mission is to provide government and commercial space ventures with pioneering technologies that enable working and living on the surfaces of the Moon, planets and other bodies in our solar system.

Capabilities & Facilities
The Swamp Works is a KSC environment designed for innovation and lean development of new space technologies, it establishes rapid, innovative and cost effective exploration mission solutions through leveraging of partnerships across NASA, industry and academia. The KSC Swamp Works was established 30 January, 2013 as a lean development environment and the philosophies aligned with those used in Kelly Johnson’s Skunk Works and Werner von Braun’s development shops. It uses a “Hands-on” approach: start small and build up fast in a helical iteration process. Testing is performed in the early stages and failures are allowed to drive subsequent rapid design improvements. Swamp Works is particularly adept at leveraging partnerships across NASA, industry & academia.

The Swamp Works consist of a group of laboratories which all have capabilities related to technology development for In-Situ Resource Utilization (ISRU) primarily leading up to Technology Readiness Level (TRL) of 6, but also capable of taking selected projects through flight implementation. The labs are:
- Applied Chemistry Lab (ACL)
- Applied Physics Lab (APL)
- Granular Mechanics & Regolith Operations Lab (GMRO)
- Cryogenics Technologies Lab (CTL)
- Electrostatics & Surface Physics Lab (ESPL)
- Corrosion Lab (CL)
- Spaceflight Physical Sciences (SPS)
- Advanced Materials and Polymer Sciences (AMPS)

The Swamp Works High Bay facility consists of 8,000 square feet of world class lab space designed to facilitate lean development processes and advanced research and technology development activities. The core facility consists of a 5,000 square foot high bay with a 40 foot ceiling height, where the original Apollo Lunar Excursion Module (LEM) simulator training occurred with the astronauts. It has since been refurbished and converted into the GMRO Lab.

The GMRO lab has supplies of various lunar regolith simulants (JSC-1A, JSC-1F, JSC-2A, GRC-3, BP-1, NU-LHT-2M, OB-1, CHENOBI) and Mars regolith simulant (JSC Mars-1 Simulant). Asteroid simulants have also been developed in collaboration with the University of Central Florida, Center for Lunar and Asteroid Surface Science (CLASS), and these simulants and preparation procedures are available for research and testing purposes. It has facilities for using these simulants in a controlled fashion in two enclosed regolith bins. One bin contains 2 tons of JSC-1A simulant and measure 6 feet x 6 feet. The second bin contains 125 tons of BP-1 regolith simulant and measures 25 feet x 25 feet x 3 feet deep. These bins are optimized for component testing, excavator tests, drilling and materials processing including additive manufacturing and construction testing. In addition the GMRO lab contains a full suite of geo-technical testing apparatus and various granular mechanics instruments. It is also equipped to develop robotic systems and includes floor space for assembly and testing as well as a small machine shop capability.

The ESPL is in a 3,000 square foot enclosed low bay area in Swamp Works and is designed to be a clean facility with a full array of surface physics equipment and a 6 foot x 3 foot x 3 foot “dirty” vacuum chamber, for regolith testing. This lab also has a small amount of valuable real Apollo Lunar regolith which is used for high fidelity selected scientific tests. The Swamp Works facility is flexible and can accommodate new projects.

The CTL have expertise and practical know-how in the area of cryogenics/materials including heat management, cryogenic-vacuum testing, experimental test protocols, instrumentation, thermal properties measurement, novel materials/composites, machinery, and process systems for below-ambient temperature applications.

Computers and software for modeling aerospace systems are available with a variety of physics based software suites. An area known as the “Innovation Space” is fully equipped for remote collaboration activities with a 3x3 (48” ea.) monitor video wall and associated computer equipment. A large bandwidth and secure internet data connection (SNRF node) is installed. White board tables, “write on” white walls and a large number of “post-it” notes enable ideation exercises and activities.

The true value of the Swamp Works lies in its personnel and their professional knowledge and skills, as well as the innovative environment and processes that allow breakthrough investigations to occur. External partnerships allow for collaborative research in multi-disciplinary endeavors. The mentality and culture in Swamp Works is one of extreme innovation and quantum leap progress with a goal of benefiting NASA and humanity in general.
**Dust Tolerant Automated Umbilical (DTAU)**

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**Introduction:**
Regolith is present on most planetary surfaces such as Earth’s moon, Mars, and asteroids. If human crews and robotic machinery are to operate on these regolith covered surfaces, then they must face the consequences of interacting with regolith fines which consist of particles below 100 microns in diameter down to as small as sub-micron scale particles. Such fine dust will intrude into mechanism and interfaces causing a variety of problems such as contamination of clean fluid lines, jamming of mechanisms, and damaging connector seals and couplings. Since multiple elements must be assembled in space for system level functionality, then it will be inevitable that interfaces will be necessary for connections to pass commodities such as cryogenic liquid propellants, purge and buffer gases, water, breathing air, pressurizing gases, heat exchange fluids, power, and data.

Dust tolerant automated umbilical (DTAU) systems which can operate in dusty planetary surfaces have been under development at NASA’s Kennedy Space Center (KSC) for a number of years. Engineering development unit (EDU) prototypes of a DTAU have been built and tested.
UNDERSTANDING COMPONENT/MATERIALS PERFORMANCE IN THE LUNAR ENVIRONMENT.
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Introduction: The lunar surface is projected to be one of the most difficult for long-term operation of mechanical systems. Extremely low night temperatures for extended periods, severe thermal gradients, periodic charging and discharging of the near surface exosphere and the highly abrasive regolith represent unprecedented challenges for the design of systems that need to operate for extended periods. Near surface transport of fine dust particles and a propensity for it to be electrostatically attached to surfaces and repel physical removal by brushing, create an environment quickly capable of degrading the performance of systems that ultimately leads to premature system failure.

Man’s desire to have a ‘permanent’ presence on the Moon has led to considerable interest and possible commercialization activities both from US and International partners [1], and in-situ, resource utilization (ISRU) promises to be a critical and potentially lucrative business for those willing to invest and adopt the significant risk associated with the development of a new infrastructure on the lunar surface. With estimated costs of $1.2M/kg to deliver payloads to the lunar surface [2], the need to understand how systems perform, develop mitigation strategies to reduce or eliminate problems and to be able to predict life performance estimates in this hostile environment, is of great importance. To this end, Southern Research and NASA’s Jet Propulsion Laboratory have been working to establish a test environment that closely approximates similar environments to those that will be encountered on the lunar surface, where materials, components and selected systems can be characterized and possible degradation mechanisms, better understood.

Materials Characterization: In an effort to provide experimental data that can be used to characterize the performance of materials/systems such as motors, actuators and small robots for instance, as well as electrostatic repulsion experiments and plasma material interactions, Southern Research has developed and instrumented a thermal vacuum chamber capable of operating at cryogenic temperatures into which simulated regolith can be introduced to mimic operating on the lunar surface. The chamber, which contains a simulated regolith base approximately 60cm by 90cm in size can routinely cycle between 100K and 400K allowing for characterization such as battery degradation through the lunar night.

The chamber will be used to characterize tribological regolith mechanisms to help design for operating in the lunar regolith, identifying selection parameters for the component building blocks such as bearings, shafts, seals, and lubricants as well as critical design methods to protect those components. New materials like bulk metallic glass and new coatings being developed by NASA for future permanent and long-duration mission applications will be characterized together with electrostatic dust repulsion systems and technologies.

References:

A critical part of any in situ resource utilization effort is storage of volatile species harvested and separated from the regolith as refined products for future utilization in a downstream process. The most obvious option for storage is compression or liquefaction of gas in a suitable tank; however, this can carry a significant penalty in terms of energy, cryogen, structural requirements, and the safety implications associated with storage of highly pressurized or liquefied dangerous gases such as hydrogen, oxygen, and hydrogen sulfide. Use of a sorbent medium in a storage vessel can lead to conversion of a portion of stored gas to an adsorbed condensed phase having higher density than the bulk gas (i.e., the Gibbs excess), dramatically increasing the storage capacity of a vessel for a given pressure and temperature. When sorption is optimized, storage densities can even exceed those of liquefying the gas (e.g., [1]). Therefore, a sought after goal for sorbent-based storage systems is to achieve liquid densities (or higher) at lower pressures and/or higher temperatures than would be possible without the sorbent. If selected for funding, our effort will evaluate high-performing terrestrial gas storage media for use in space, as well as explore whether lunar regolith can be modified to be an operationally-useful storage medium. The key parameters are storage capacity, energetics, and kinetics for a given gas-solid combination.

Whether a carefully designed sorbent material is brought from Earth, or modified lunar regolith itself provides the sorption medium, no sorption powder can operate without supporting hardware (e.g. pressure vessel, valves, tubing) and systems (e.g. compressors, heating, chilling). Therefore, if selected for funding, we will also evaluate the systems necessary for volatiles storage and build a scaled-up laboratory ISRU storage demonstration.

**ELECTROSTATIC BENEFICIATION OF LUNAR REGOLITH: A REVIEW OF PREVIOUS TESTING AS A STARTING POINT FOR FUTURE WORK.** J.W. Quinn, NASA Kennedy Space Center, Applied Sciences Branch, Mailstop UB-R3-A, KSC FL. 32899  Jacqueline.W.Quinn@nasa.gov.

**Introduction:** When NASA pivoted away from the Moon in 2008, much of the lunar In Situ Resource Utilization (ISRU) research was shelved. However, with the Agency’s renewed lunar interest, long-abandoned research has begun anew, including work associated with lunar regolith enrichment, or beneficiation. In addition to oxygen and water necessary for human life, resources are needed to build habitats, landing/launch infrastructure and to provide radiation protection. Many of these needs can be addressed using regolith already present on the surface, as it contains sufficient minerals and metal oxides to meet the requirements. However, before processing the regolith, it would be most cost and power effective if the regolith could be enriched for the mineral(s) of interest. This can be achieved by electrostatic beneficiation in which tribocharged mineral-particles are separated out and the feedstock enriched or depleted as required.

**Background:** Lunar regolith is a product of eons of volcanic activity and micro-meteorite bombardment, resulting in a covering of fine dust composed of minerals containing oxides of major metals such as aluminum, iron, titanium, magnesium, and sodium as well as oxides of elements such as silicon, calcium and potassium. These elements are present in minerals such as anorthite, olivine, spodumene, ilmenite, and various feldspars and glass agglutinates[1]. In addition to structural uses of lunar regolith, there are several chemical processes capable of extracting oxygen from the regolith including molten oxide electrolysis and hydrogen reduction [2]. Whatever the application, building materials or water and oxygen production, different concentrations of the composing elements are required, and considerable cost in time and energy would be saved if the desired minerals were more highly concentrated in the feedstock before processing. In the case of oxygen production, the mineral ilmenite (FeTiO3) is of interest as it is more energetically favorable for extraction [3], [4]. Hydrogen reduction of Ilmenite has the potential to yield up to 10.5% oxygen [5] and therefore, enrichment of ilmenite in the lunar regolith feedstock is desirable.

Triboelectrification and electrostatic beneficiation of minerals using a parallel-plate separator is a well-known technology successfully used to separate coal from minerals [6], quartz from feldspar, phosphate rock from silica sand, and phosphorus from silica and iron ore [7]. Lunar regolith, with its lack of moisture and low electrical conductivity and dielectric losses, is an ideal candidate for triboelectrification and electrostatic separation.

**Previous Testing Reviewed:** Tribocharged beneficiation testing initiated in air using NU-LHT-2M simulant, followed by similar testing in lunar vacuum conditions. Additionally, reduced gravity flights in atmosphere were also conducted using lunar simulants and similar electrostatic tribocharging materials. With favorable results achieved in air, in vacuum and in reduced gravity using lunar simulants, testing progressed to include evaluation with Apollo 14 and Apollo 17 regolith. Summary results of electrostatic beneficiation of lunar simulants and actual Apollo regolith are presented in which various degrees of efficient particle separation and mineral enrichment up to a few hundred percent were achieved. Synopsis data presented serve as a starting point for reinitiating beneficiation research.

**References:**

**Introduction:** Volatiles on the Moon are far more abundant than even optimistic estimates had predicted prior to numerous discoveries made in 2009. This inventory includes not only water ice, but other constituents such as hydrogen sulfide, ammonia, carbon monoxide, and methane. In-situ resource utilization (ISRU) of such species offers exciting possibilities to enable sustainable exploration endeavors within cis-lunar space. Our IS$^5$ concept study proposed in response to SSERVI CAN 3 focuses on lunar ISRU science and technology development and is structured around five themes: Scouting, Sampling, Separation, Synthesis, and Storage. Within each theme, we pursue basic science, laboratory research, and hardware advances to develop modular subsystems for integration into our virtual pilot ISRU System of Systems (SoS) testbed, a precursor to future ISRU systems capable of mission consumables production from native volatiles and regolith on the lunar surface.

We envision IS$^5$ to provide a collaborative platform for ISRU specialists, materials engineers, experimentalists, modelers, and remote-sensing experts to work together to generate precise lunar volatile abundance maps, execute key experiments to constrain physico-chemical properties of lunar regolith and volatiles, and develop hardware to advance innovative ISRU concepts for volatile identification and reactivity assessment, extraction, storage and utilization. IS$^5$'s Scouting theme will focus on cross-comparative syntheses of mapping datasets from multiple instruments on missions like the Lunar Reconnaissance Orbiter to constrain the abundance and spatial distribution of volatiles at ISRU operation scales, while synergistically advancing our understanding of the lunar volatile cycle. SwRI’s Mechanical Engineering and Space Science Divisions will join forces with academic, government and industry, especially Commercial Lunar Payload Services partners to explore volatiles sampling and extraction instrumentation/techniques, and in particular, pursue TRL advancement of the lance probe of VAPORR (Volatiles Analyzer and Prospector of Regolith Resources) instrument concept within the Sampling theme. The Separation theme will develop the physics to model the heat transport, phase change, and gas diffusion in the regolith, and mature novel thin film membrane technology for volatile separation and purification. Our Synthesis theme will advance non-equilibrium plasma technologies to produce polymer precursors from volatile feedstocks for use as solid propellants and cohesive binders for compounding with dry regolith to enable 3-D printing applications, spearheaded by our international/commercial partners. Our sorption science experts will investigate adsorption capacity of ultra-high surface area materials such as MOFs, PPNs as well as activated lunar soil as storage media for extracted volatiles within the Storage theme. Additionally, we will design and develop hermetically-sealed storage canisters with thermal management considerations to enable pristine sample return from impact basins or permanently shadowed regions by future missions.

The underlying motif of our IS$^5$ proposal is to advance ISRU technologies for lunar exploration. The Moon is the next logical destination for continued robotic/human exploration of the solar system. The ISRU research pursued in each theme is directly traceable to the priorities of the lunar exploration roadmap (LER) and should incrementally enable closure of several NASA’s open lunar SKGs. The IS$^5$ objectives are well-aligned with the priorities of the current administration for renewed American leadership in lunar exploration, including “boots on the ground”, and NASA Strategic Plan 2018.
THERMOGRAVIMETRIC ANALYSIS OF THE REDUCTION OF IMENITE AND NU-LHT-2M WITH HYDROGEN AND METHANE. P. Reiss1, F. Kerscher2 and L. Grill1, 1Technical University of Munich, Institute of Astronautics, Boltzmannstr. 15, 85748 Garching, Germany (p.reiss@tum.de), 2Technical University of Munich, Institute for Energy Systems, Boltzmannstr. 15, 85748 Garching, Germany.

Introduction: The majority of past studies on oxygen production from lunar regolith has been focussing on the chemical reduction of the regolith using hydrogen as a reactant gas. Another process that has often been discussed for producing oxygen from lunar regolith is the chemical reduction with methane. In the past, these reduction processes have been studied theoretically and experimentally on different scales, with different sample materials, and different process conditions. Although both processes have different characteristics and requirements, it is not entirely understood to what extent the reactant gases could potentially be replaced with each other in an ISRU reactor and what the implications in terms of oxygen yield, reaction rates, and by-products are depending on the feedstock. For an ISRU reactor it is advantageous to avoid temperatures in the melting range of lunar regolith, above 1100 °C [1]. It is questionable if and how well the reduction with methane works below this temperature. To enable the evaluation and selection of ISRU processes on a common basis we performed a direct comparison of the above processes under the same reaction conditions by means of thermogravimetric analysis (TGA).

Materials and methods: The investigated samples were 93-96 % pure ilmenite (FeTiO3) as a reference with good susceptibility to reduction and the lunar regolith simulant NU-LHT-2M as a chemically analogue for (polar) highland regolith. They were sieved to the 100-125 μm size fraction to make sure that the ilmenite particles in NU-LHT-2M are included in the sample [2]. The apparatus used for thermogravimetric analysis was a Linseis STA PT 1750. Samples with a mass of 70-80 mg were heated in a flow of nitrogen, hydrogen, and methane at 200 ml/min with a heating rate of 6 °C/min from room temperature to 1000 °C.

Results with hydrogen: The ilmenite sample showed a significant weight loss of 12.7 % between 500 °C and 850 °C due to the reduction with hydrogen, slightly larger than the the stoichiometrically expected weight loss of 10.5 %. An ilmenite sample that was baked out under nitrogen beforehand yielded a similar weight loss of 12.6 %. For the NU-LHT-2M sample a weight loss of 0.7 % was measured between 550 °C and 700 °C. Another NU-LHT-2M sample that was baked out under nitrogen beforehand yielded a weight loss of only 0.2 % between 650 °C and 700 °C. This corresponds well with the expected stoichiometric weight loss for an ilmenite content of 1.5 % [2]. The higher weight loss measured for the first NU-LHT-2M sample is caused by additional thermal decomposition products, such as water, carbon monoxide, and carbon dioxide [3]. Potential side reactions with these products complicate the interpretation of the weight change measured via TGA because they are on the same order as the expected weight loss due to reduction of the ilmenite content. Therefore it is recommended to bake out NU-LHT-2M before using it for ISRU preparation studies. An additional observation was that the NU-LHT-2M treated with hydrogen noticeably changed its visual appearance from white or bright grey to dark grey (Figure 1). This most likely is because of a chemical alteration of plagioclase, which makes up ~60 % of the sample.

Results with methane: In order to serve as a reactant, methane needs to be decomposed into hydrogen and carbon. This can happen at temperatures as low as 700 °C to 800 °C [4]. While the hydrogen in gaseous form can readily react with the sample, the solid carbon deposits on the sample first to enable the reduction at higher temperatures. Correspondingly, the TGA shows two subsequent weight losses for the ilmenite sample, 1.5 % at 550-900 °C and 5.5 % at 900-915 °C. A sample that was baked out under nitrogen beforehand shows a similar weight loss of 1.8 % at 700-910 °C and 6.5 % at 910-940 °C. At temperatures above 915 °C and 940 °C respectively, there is strong deposition of carbon, which overcompensates any further weight loss through reduction. The NU-LHT-2M sample did not exhibit a significant weight change under methane besides the expected weight loss due to thermal decomposition of the minerals and the strong weight increase due to carbon deposition above 900 °C. Again the potential side reactions with decomposition products complicate a clear identification of the reduction processes of the sample.

Fig. 1: NU-LHT-2M (100-125 μm) before and after TGA

**Introduction:** Drilling for volatile materials is of particular interest in the lunar polar regions. Accumulation of triboelectric charge can pose a substantial challenge to exploration equipment in a lunar polar crater, which provides few sources of charge dissipation [1]. With a highly insulating surface and no direct access to solar photoemission or solar wind, the main source of grounding in this permanently shadowed region is the tenuous residual plasma from a solar wind wake [2].

The present study applies a new plasma wake model to characterize the crater electrical environment [3] and examines implications for triboelectric charge accumulation on human equipment while drilling in the lunar regolith. We present predictions for the rate of charge accumulation, for different triboelectric material properties. Two possible solutions for regulating charge accumulation are (i) artificial UV radiation and (ii) extended wiring to the neutral region.

As a secondary implication of the triboelectric charging of equipment interacting with the lunar regolith, we examine lofting of tribo-charged dust grains. We predict the steady-state dust cloud levitation effects in a plasma-generated electric field.

A brief illustration of these results is presented below.

**Electrical environment characterized by plasma wake:** As the solar wind flows over a crater on an airless body, the resulting non-neutral plasma wake creates a non-neutral region known as the electron cloud (Fig. 1). Owing to low surface conductivity, the diffuse electrons provide the sole source of electrical grounding in this region, and only for positively charged objects. Farther downstream, the quasi-neutral plasma wake arrives at the surface and provides grounding for both positive and negatively charged objects.

**Charge accumulation on drill differs across plasma domains and triboelectric material properties:** A preliminary analytic calculation (based on Ref. [1]) of the electric potential on a drill – relative to the surface – shows substantial difference between the electron cloud and the quasi-neutral region. Equally important are the triboelectric properties of the drill and lunar regolith. Fig. 2 presents four different charge accumulation scenarios, based on the drilling location and materials.

**Dust cloud steady-state may result from drill ejecta:** In the case where the drill charges positive and the dust negative, ejected grains can be caught in the electric field created by the plasma wake. Results in Fig. 3 suggest that the typical micron-size grains may aggregate near the upper leeward edge, where the solar wind enters the crater.

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**Fig. 1:** Electron cloud density characterizes electrical grounding in a lunar polar crater.

**Fig. 2:** Drill potential relative to surface, for different location and triboelectric material properties.

**Fig. 3:** Dust cloud steady-state grain size distribution, resulting from a positive-drill negative regolith charge exchange.

BEYOND ROVERS: MOBILITY FOR LUNAR ISRU. Gordon Roesler, Robots in Space LLC, Annapolis, MD, robotsinspacellc@gmail.com.

Abstract: Robotic mobility for a robust ISRU facility, in the extraction and processing phases, has a fundamentally different character from mobility in the exploration phase. Unlike the operations of planetary rovers, many of the ISRU mobility tasks are repetitive; others require delivery; still others are defined by lift, mechanical manipulation and joining. In addition, the environment presents obvious challenges: temperatures of tens of Kelvins, abrasive regolith, random obstacles of random sizes. Self-powered vehicles are hard-put to carry sufficient energy for the speed and range necessary for efficient facility operation. It is also important to minimize appurtenances such as solar panels or microwave receivers on the robotic vehicles, so as not to interfere with the robotic workspace. A mobility approach that provides some mitigation for all of these challenges features elevated tracks. Strong, lightweight tracks can be self-emplaced by robotic vehicles, permitting dust-free travel, simplified navigation, and reduced wheel wear. Low-loss electrical conductors incorporated in the tracks can alleviate energy constraints on vehicle and manipulator operation, eliminate appurtenances, and facilitate communications and control. Vehicles designed for tracked operation can have simplified suspensions, and can be designed compactly to reduce heat losses. A conceptual vehicle and track co-design and operations approach will be presented.
MODELLING PROSPECTIVITY OF UNDER EXPLORED REGIONS: DEPLOYING ORE SYSTEM BASED PREDICTIONS IN A LUNAR ENVIRONMENT. N. Rogers and M. E. Villeneuve, Geological Survey of Canada, Natural Resources Canada, 601 Booth Street, Ottawa, Ontario, K1A 0E8, Canada (mike.villeneuve@canada.ca).

Introduction: A fundamental challenge of conducting resource exploration in frontier regions, whether in northern Canada, deep underground or on the moon, is knowing where to begin the search. Direct detection of resources is cost prohibitive and so, the goal of frontier exploration is to identify the most prospective areas within which to target efforts. The ore system concept focuses on processes related to the genetic, depositional and post-depositional, which in turn provides a series of markers that form a larger footprint of a deposit. For an economically viable deposit, whether gold on earth or water on the moon, in addition to a target area having anomalously elevated contents of a desired resource, the resource needs to be hosted in a readily extractable form. As the ore system concept incorporates all the processes relating to resource development, it can also facilitate targeting the most easily extractable deposits.

Mineral Prospectivity Mapping: Mineral prospectivity mapping represents the application of rule-based assessments to delineate target areas that most likely (or conversely, aren’t likely) to contain mineral deposits. The traditional approach to assessing the prospectivity of an area is by making a qualitative opinion based on experience, deposit models and public geoscience knowledge. Such an approach, although subjective, can be effective in some circumstances, but is inherently limited in frontier regions. Alternate approaches, such as weights-of-evidence models or knowledge-driven fuzzy logic probabilities of defined deposit types, have been developed in order to produce more rigorous, consistent and quantitative analysis [1], [2], [3], [4]. More recently, improvements in artificial intelligence and data handling are enabling advanced GIS-based machine learning to integrate process related ore system knowledge with weighted predictors. An example of such an approach is Geoscience Australia’s ‘Mineral Potential Mapper’: a computer-based quantitative prospectivity modeler that ‘data mines’ multiple, national-scale geoscientific spatial datasets for indicators of ore system processes [5].

Prospectivity of New Frontiers: Current methods of quantitative prospectivity mapping have operational limitations in frontier domains as they tend to breakdown where data is sparse and heterogeneously distributed. They are also intrinsically representative, rather than truly predictive, in the sense of being able to infer prospectivity assessments into unknown regions. Furthermore, as mineral systems represent atypical features, data outliers can be positive indicators for presence or absence of resources. Unfortunately erroneous data is also liable to appear as an outlier. In data rich environments, the impact from occasional erroneous data is compensated for by the sheer mass of data. However, in sparse data scenarios (such as the frontier regions) the impact could be substantive.

Conclusion: The need for additional resources will continue to push exploration into frontier regions. For lunar resource exploration, the challenges maybe extreme and target materials (at least initially) different from Canadian mineral exploration, but the same principles apply whereby ore system models can direct exploration activities to prospective areas. Advancements in artificial intelligence offer the potential for improved prospectivity models for regions, such as the moon, that have sparse and heterogeneously distributed data. The prospect of being able to effectively target areas on the moon suitable for resource extraction will be a major factor in fomenting viable lunar mining.

Regolith Extraction Through Molten Regolith Electrolysis

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Introduction:
Molten oxide electrolysis (a.k.a. magma electrolysis) is an extreme form of molten salt electrolysis, a technology that has been producing tonnage metal for over 100 years; aluminum, magnesium, lithium, sodium, and the rare-earth metals are all produced in this manner. What sets molten oxide electrolysis apart is its ability to directly electrolyze regolith as-received to produce pure oxygen at one electrode and a plurality of liquid metals at the other electrode, doing so without the need for any form of supporting electrolyte.

Figure 1 shows a schematic of such a reactor. The passage of electric current through the molten regolith drives electrochemical reactions at the electrodes producing oxygen at the anode and liquid metal at the cathode. In parallel, this electric current generates joule heat in the molten regolith so as to maintain the operating temperature. By tuning the insulation at the sidewall the temperature is made to fall below the freezing point of regolith enabling the melt to be contained within a frozen skull of same. Oxygen evolves continuously from the top of the cell. Liquid metal collects at the bottom of the cell from which it is periodically removed either by bottom tapping or siphoning. The composition of the metal product is a function of the composition of the regolith feedstock and the operating conditions, including cell current and temperature. Multicomponent liquid metal alloys can be subsequently refined in a secondary electrolysis cell. Among the metals present are Fe, Si, Al, Mg and Ca, which can be utilized to fabricate in-situ power grids, radio observatories, and other surface assets.

References:

Introduction: ProSPA forms part of ESA’s Package for Resource Observation and in-situ Prospecting for Exploration, Commercial Exploitation and Transportation (PROSPECT) which is to be used in a high latitude region of the Moon in ~2023 [1]. In addition to determining the lunar volatile inventory, ProSPA will perform a proof-of-principle ISRU water extraction experiment on the lunar surface on samples of ~50 mg.

It is of interest to obtain water, and its associated oxygen and hydrogen, on the Moon in order to meet the needs of crewed exploration missions to the lunar surface, and beyond. Frozen water is likely located in hard-to-reach polar regions, so other sources of water are being considered. Ilmenite, a common lunar mineral, can be reduced with hydrogen to produce water. This work considers the temperature and pressure constraints of an ilmenite reduction reaction performed using a static system, suitable for use on ProSPA.

Ilmenite Reduction: Hydrogen can reduce ilmenite to produce water in an equilibrium reaction as follows:

\[ \text{FeTiO}_3 + H_2 \rightarrow \text{Fe} + \text{TiO}_2 + H_2O \]  

(1)

Ilmenite reduction can be performed at relatively low temperatures of 700-1000°C [2]. This is within the operating constraints of ProSPA. However, the reduction reaction is usually performed in a flowing stream of hydrogen which removes water from the reaction site [3,4]. As a consequence of the static nature of the ProSPA design, a cold finger is used to condense the produced water [5]. A benchtop demonstration model (BDM), used to simulate the ProSPA design, has successfully been used to reduce ilmenite in a static system, trapping and quantifying the produced water [6]. The BDM reduced ilmenite samples (up to 45 mg) at 900°C for 1 hr. Although water was produced from these studies, the reactions did not complete. A new system design was developed with improved thermal control, and is known as the ISRU-BDM. The new system has been used to perform ilmenite reduction tests for a range of temperatures and pressures.

Materials and Methodology: The ISRU-BDM is a sealed vacuum system that operates inside a uniformly heated box at 120°C. A furnace that can reach >1000 °C heats a 4 mm i.d. ceramic sample holder. The cold finger is thermally controlled by heaters and a supply of cooled nitrogen gas.

For each experiment 45 mg (0.3 mmol) of 95% pure ilmenite (average grain size of 170 μm) is baked out to 500°C for 1 hr [6]. Then the desired quantity of hydrogen (120, 210, 345, 420, 580 mbar) is added to the system. The furnace is then heated to the desired temperature (850, 900, 950, 1000, 1050, 1100°C) for 4 hours and any produced water is condensed at the cold finger which operates at -80°C. Finally, the cold finger is heated to 120°C and water released as a vapor. Pressure readings are recorded during each experiment to monitor the reaction and its products.

Results: Preliminary results have shown that with increasing temperature the reaction produces increased quantities of water. When ilmenite is in the solid phase, the maximum yield is 3.40±0.07 wt.% O2 for a reaction temperature of 1000°C. When heating beyond the melting point of ilmenite, the maximum yield is 4.42±0.08 wt.% O2 for a reaction temperature of 1100°C. Hydrogen pressures have a twofold effect on the reaction rate. Initially, lower pressures (<120 mbar) are favorable as the produced water easily diffuses through the system to the cold finger. As the reaction proceeds into the grain higher hydrogen pressures (~420 mbar) are required to enable penetration into the grains. SEM and XRD analysis supports the results obtained.

Conclusions and Future work: A static system can successfully produce water from the hydrogen reduction of 45 mg ilmenite. Yields can be calculated from the change in gas pressure, where the maximum yield is obtained at higher temperatures. The required hydrogen pressure should be tailored to the design of the system with low pressures at the start of the reaction followed by higher pressures as the reaction proceeds. Although a static system is not optimized for an ISRU reaction, it is a simple technique that can be used to perform a proof-of-principle reduction reaction of lunar ilmenite in situ.

Future work will consider if the system can be used to produce water from the reduction of lunar meteorites and Apollo samples.


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Introduction: Lunar Pyroclastic deposits (LPDs) and Permanently Shaded Regions (PSRs) are areas of the Moon that have significant ISRU potential. LPDs can contain volatile- and ilmenite-rich glasses [1,2], whilst PSRs act as cold traps for stable water ice [3,4]. Although several proposed missions may explore these regions, little is known about trafficability of those terrains. Here we used boulder tracks to remotely determine the bearing capacity of regolith in representative sites within LPDs and PSRs.

Lunar boulder tracks: Rockfalls and their associated boulder tracks are abundant on the Moon. They are also classic tools for determining surface properties, having been used during Apollo to evaluate bearing capacities at the Apollo 17 landing site. The key input parameters are boulder and track dimensions, and those of their associated shadows, which can be evaluated as a function of slope and boulder shape using Hansen’s formula [5].

Methods: Forty-eight boulder tracks in 10 large LPDs [6] and 13 boulder tracks in 5 PSRs [7] were identified. A baseline set of boulder tracks in highland and mare regions was also measured. Whilst measurements for boulders in LPDs, highland, and mare regions can be made directly from NAC imagery, that is not possible in PSRs. For those regions, NAC images were stretched by enhancing contrast and brightness to identify boulder tracks in shadowed areas. Only areas that experience secondary sunlight, diffusively reflected from crater walls into PSRs, could be used in this study as some secondary source of illumination was required to identify boulders.

After suitable images were selected, they were processed to remove excess noise. Boulder and track dimensions, and the associated shadows produced, were recorded. All measurements and complementary soil properties from the literature were then input into Hansen’s formula to estimate bearing capacities.

Results: Qualitative analyses show that boulder tracks formed in LPDs and PSRs have similar morphologies to those formed in highland and mare regions. Bearing capacity decreases with increasing slope across all location types. Therefore, rover wheels and lander pads will sink more on steeper slopes [5]. LPDs and PSRs are significantly stronger than mare regions in almost all depth ranges of regolith with estimated bearing capacities of 131±21 kNm² and 127±29 kNm² respectively, compared to 85±12 kNm² for mare regions (for upper 1 m on 0° inclines). There was insufficient data in the upper 1 m of highland regolith for comparison. It should be noted that this technique is limited by the minimum depth of measured boulder tracks (≥19 cm in LPDs, which is limited by the resolution of the available NAC imagery (~0.5 m/pixel).

Combining our results with data obtained from surface images of lunar rover tracks, and extrapolating to the upper few cm’s of regolith, suggests that rovers and landers planning to explore LPDs should not sink as far into the regolith there as in highland and mare regions. The nature of the uppermost 28 cm of PSRs (the minimum track depth measured in PSRs) remain unclear as a result of special environmental conditions.

Conclusions: This initial study of boulder track analyses suggests the regolith in LPDs and PSRs is significantly stronger than mare regolith at equivalent depths of ≥ 19 cm and 28 cm respectively. Trafficability should not be an unusually difficult impediment to ISRU within LPDs, meanwhile the trafficability of rovers in PSRs remains uncertain. To further reduce mission risk, the soil strength calculated here for LPDs and PSRs should be tested in situ.

Acknowledgements: Thank you for the support and funding from USRA-LPI and CLSE.

EXPERIMENTAL STUDY AND MODELING OF GAS TRANSPORT WITHIN REGOLITH FOR EXAMINING ISRU/SAMPLING SCENARIOS. G. L. Schieber1, B. M. Jones2, T. M. Orlando2, P. G. Loutzenhiser1, 1George W. Woodruff School of Mechanical Engineering and 2School of Chemistry and Biochemistry, Georgia Institute of Technology

Introduction: Understanding gas transport within regolith is important for both fundamental and applied science applications. A basic understanding is required as it allows for predictive modeling and provides the foundation for examining different scenarios involving in-situ resource utilization (ISRU) and sample collection during extended missions to near Earth destinations such as the Moon. The design of thermal H2O extraction devices requires a fundamental understanding of gas transport within regolith, at pressures not yet studied [1, 2]. This work considers the flow of noncondensing gases (Ar, N2) as a first step towards ultimate study of more intricate interactions between molecules with permanent dipoles and regolith, namely H2O. The goal of this work is to experimentally assess the properties of porous media and gas species that impact transport, providing an experimental validation to the commonly applied advection diffusion model for low pressure H2O transport within lunar regolith.

Theory: The Knudsen number (Kn) is defined as the ratio of the mean free path to a length scale and represents the relative likelihood of molecular collisions with other gas molecules or with a solid surface. For Kn << 1, the flow is dominated by intermolecular collisions, and is assumed to behave in a continuum. The flow for Kn >>1 is dominated by wall-molecular collisions where the continuum assumption does not capture the phenomena [3]. The flows can be divided into four different regimes: (1) continuum (Kn<10^{-2}), (2) slip (10^{-2}<Kn<10^{-1}), (3) transition (10^{-1}<Kn<10), and (4) Knudsen (Kn>10) regimes [4]. In this study, three regimes, were experimentally examined: (1) the slip flow regime, (2) the transition regime, and (3) the Knudsen regime, corresponded to average N2 pressures of 100 to 30,000 Pa within a packed bed of JSC-1A regolith simulant at ambient temperature. These regimes are relevant to both ISRU and sampling missions.

Results: The results indicate that the advection diffusion model fit the data when Kn<1 and began to deviate when Kn>1. Based on the results for the Knudsen regime, the predictive model for Knudsen diffusivity corresponded well to experimental measurements as the average Kn approached 10. Model refinement would be provided by further study to determine a relationship for tortuosity of non-uniform packed beds of particles. An investigation of tortuosity is underway, utilizing the computational method as outlined in Sobieski et. al [5].

Conclusion: This study has evaluated gas flow with in a lunar relevant porous medium and provides the framework for moving to more complex volatiles such as H2O. We show that the advection diffusion model, typically applied to bulk volatile transport for ISRU, needs to be verified, as even for the simplified case presented, model improvements are necessary. If thermal extraction of H2O for ISRU is to be realized, a model for the transport of the evolved volatiles is a critical component for system design.


Acknowledgements: This work was carried out as part of REVEALS which was directly supported by the NASA Solar System Exploration Research Virtual Institute cooperative, agreement number NNA17BF68A.
COMMON POOL LUNAR RESOURCES. J. K. Schingler and A. Kapoglou, 1Open Lunar Foundation, jessykate@openlunar.org, 2UCL Institute for public purpose and innovation, a.kapoglou@ucl.ac.uk.

Introduction: Article II of the 1967 Outer Space Treaty (OST) famously asserts that the Moon and other celestial bodies are “not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means.” [1] The question of how to honor Article II in the face of near future in-situ resource utilization, and how to do so in a way that encourages the sustainable development of economic activity, remains an active topic of discussion. Article II has been variously interpreted as prohibiting sovereignty, ownership, and even resource extraction, on the Moon.

A Conceptual Schema for Property Rights: Part of the challenge in coming to agreement about Article II is imprecise terminology, and lack of a shared framework for discussion. Ostrom and Schlager [2] offer one framework that distills the broad concept of property rights into 5 different “bundles” of rights, each of which are associated with rules and obligations. These rights are categorized as operational level rights (access, withdrawal) and collective-choice rights (management, exclusion, and alienation).

Although many of the major space-faring states have a practice of associating property rights with what Ostrom and Schlager refer to as the collective-choice right of “alienation,” or the right to “sell or lease... [other] collective choice rights,” there are a multitude of property rights regimes that can and have been applied to the management of withdrawal rights, without incorporating the right of alienation [3].

Part I of this article applies the conceptual schema proposed by Ostrom and Schlager to the context of lunar resources under the Outer Space Treaty, and shows that it can be used to structure a more precise conversation about resource utilization on the Moon (access and withdrawal). Further, this schema introduces an important new dimension to the conversation: namely, the design of collective-choice rights. We provide examples of how this schema can be used to construct property rights regimes for the Moon, and show that complete regimes exist which also honor Article II of the OST.

Common Pool Resources: Common Pool Resources (CPR) theory is a specific approach to resource management explored in detail by Ostrom and her colleagues. CPRs are characterized by subtractability, where it is difficult or costly to exclude other users from leveraging a resource.

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<th>EXCLUSION</th>
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<tr>
<td>Difficult</td>
<td>Public goods</td>
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<td>Journal subscriptions</td>
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<td>Day-care centers</td>
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Figure 1: Types of Goods [4]

Part II of this paper argues that the benefit sharing and non-appropriation clauses of the OST (Articles I and II) provide a strong argument for considering resources on the Moon as Common Pool Resources, which roots them in a long tradition of resource management schemes on Earth including water management, grazing lands, and fisheries; and provides a strong starting point for selecting between the vast option space for property right regimes outlined in Part I.

Resource management regimes are important for efficient, effective, and enduring operations, and can operate as confidence-building mechanisms for state actors and commercial investors [3]. We argue that CPR theory can be used to design resource management frameworks for the Moon that balance the needs of commercial, state, and civic actors.

LUNAR HELIUM-3 AS THE FOUNDATION OF LUNAR AND MARS SETTLEMENT AND A EARTH-MOON ECONOMY. H. H. Schmitt

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Introduction: The fusion of lunar $^3$He with itself or with $^2$H (deuterium) offers the promise of environmentally benign electrical power on Earth and flexible and rapid interplanetary propulsion. [1,2] $^3$He-$^3$He fusion specifically holds the promise of nuclear power without nuclear waste. A spinoff of this technology also can provide access to short-lived medical isotopes that expand access to positron emission tomography (PET). Further, the $^2$H, $^2$H$_2$O, $^4$He, C, N$_2$ and O$_2$ by-products of lunar $^3$He production that enable lunar settlement and Mars exploration as well as the ultimate initiation of the settlement of Mars. The long-term geopolitical potential of lunar $^3$He is well recognized and may stimulate economic competition in deep space.

Financial Envelope: The financial envelope for $^3$He fusion to be approximately competitive with steam coal or natural gas priced at \$2.50/million BTUs (equivalent to $1.4M/kg of $^3$He) consists of the following:

- Demonstration of $^3$He fusion’s commercial viability - $5B private investment.
- Demonstration of launch costs to the Moon of \$3000/kg - \$5B private investment.
- Establishment of a lunar settlement with capability of production of 100 kg/yr of $^3$He - $2.5B private investment.
- $2.5B (17\%)$ management reserve

Space Law: Currently applicable Space Law, the Outer Space Treaty of 1967, is permissive relative to the “use” of lunar resources, provided the activity is licensed by a signatory state. [2] Although the signatory state has legal jurisdiction over the activities of its licensee, the Outer Space Treaty does not provide a definition of a claim regime that would provide orderly relations between resource competitors. Such a regime could be established between interested states without renegotiation of the Treaty.

Conclusion: The most efficient means of realizing lunar and mars settlement would be private investment in a Earth-Moon economy based on $^3$He fusion and the utilization of by-products from lunar $^3$He production. Additional benefits of such investment would be flexible and rapid interplanetary propulsion and the availability of short-lived medical isotopes for PET diagnostics.

RASSOR, the reduced gravity excavator. J. M. Schuler\textsuperscript{1}, J. D. Smith\textsuperscript{2}, R. P. Mueller\textsuperscript{3}, and A. J. Nick\textsuperscript{4}, \textsuperscript{1,2,3} NASA, Kennedy Space Center (Mail Stop: UB-R1, Kennedy Space Center, FL 32899, jason.m.schuler@nasa.gov, jonathan.d.smith@nasa.gov, rob.mueller@nasa.gov), \textsuperscript{4} Bionetics, Kennedy Space Center (Mail Stop: LASSO-001, Kennedy Space Center, FL 32899, andrew.j.nick@nasa.gov)

Introduction: Lunar regolith is full of resources that can enable a sustained human presence on the moon. Oxygen can be found in abundance and can be used for breathing air and rocket propellant. The regolith can be used as an in-situ building material for constructing infrastructure. Metals can be extracted and used to produce spare parts.

But before we can use this valuable regolith we need to excavate it. An excavator will need to be low mass to meet launch and landing payload requirements and it will operate in a 1/6G environment. The challenge is this: how can we generate enough reaction force to excavate regolith with such a lightweight vehicle? One solution is the Regolith Advanced Surface Systems Operations Robot (RASSOR); a robotic mining vehicle designed to operate in low-gravity environments.

Capabilities: RASSOR utilizes digging tools called bucket drums that have small staggered scoops around a central hollow cylinder. The scoops direct the regolith into the bucket drum and through a series of baffles. The baffles ensure that the regolith is trapped inside the drum as long as the direction of rotation is maintained. The regolith can then be transported to the appropriate site and then dumped by simply reversing the direction of rotation of the drums.

The bucket drums reduce excavation forces because of their small scoops however this isn’t enough. To ensure that the vehicle’s weight is not the main source of reaction force, RASSOR uses two sets of bucket drums that dig in opposing directions. The primary excavation forces from these drums cancel out enabling this small excavator to collect significant amounts of regolith.

Additionally, the bucket drums on RASSOR are positioned at the ends of actuated arms to precisely control the digging depth while driving over uneven terrain. These arms happen to also provide RASSOR with unique mobility capabilities. RASSOR’s configuration allows it to right itself if flipped onto its back or side, stand-up to reach into tall hoppers, climb obstacles up to 75cm (29.5in) tall, and use the bucket drums as a second set of wheels for contingency operations.

Technical Information: The following table provides key technical parameters for the latest generation of RASSOR (TRL 4) built at Kennedy Space Center:

<table>
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<th>Table 1. Key Technical Parameters</th>
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<tr>
<td>Power source</td>
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<td>Battery capacity</td>
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<tr>
<td>Max driving slope</td>
</tr>
<tr>
<td>Max obstacle height</td>
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<tr>
<td>Regolith delivered/trip</td>
</tr>
<tr>
<td>Max speed</td>
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<tr>
<td>Trips/charge (100m)</td>
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<tr>
<td>Dry Mass</td>
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<tr>
<td>Energy/Delivered Regolith</td>
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Figure 1. RASSOR excavating a slot trench in BP-1

Figure 2. Traversing max obstacle

Next Steps: Future work to increase the TRL of RASSOR will include: thermal management system development, flight-like material selection, thermal-vacuum testing, design lifetime considerations.
COMBUSTION-BASED METHODS FOR CONSTRUCTION ON THE MOON. E. Shafirovich, Department of Mechanical Engineering, The University of Texas at El Paso, 500 W. University Ave., El Paso, TX 79968, USA, eshafigrovich2@utep.edu.

It is widely agreed that lunar regolith will be used as a construction material on the Moon. However, consolidation of regolith by conventional methods, such as microwave heating [1, 2], requires a significant energy input. An alternative approach for consolidating regolith involves mixing it with energetic additives that can react either between each other or with the regolith, leading to the formation of ceramic materials. The use of chemical energy stored in reactants dramatically decreases the required external energy input and only a small amount of energetic materials is required. Also, energetic metals, such as aluminum and magnesium, could be recovered from regolith [3-5] or by recycling foil, propellant tanks, and other parts.

Studies on combustion of lunar and Martian regolith simulants with magnesium were conducted at the University of Texas at El Paso (UTEP) [6-10]. This research included thermodynamic calculations, combustion experiments in an argon environment at normal and reduced gravity, and thermoanalytical studies of the reaction mechanisms. The results indicate that magnesium is an effective additive that enables a self-sustained combustion of regolith-based mixtures (Fig. 1) through thermite reactions with regolith constituents such as silica and iron oxide.

Fig. 1. Combustion propagation over compacted mixture of JSC-1A lunar regolith simulant with magnesium; pellet diameter: 25 mm [8].

Combustion approaches could also be used for joining regolith items fabricated in situ by other methods. Researchers at NASA Kennedy Space Center have developed sintering techniques for converting regolith into ceramic tiles that are sufficiently strong, survive rocket plumes, and can be assembled into a launch/landing pad [11-13]. It is unclear, however, how to reliably join the tiles in such a pad with relatively small amounts of energy and materials.

Experimental and modeling studies have been conducted at UTEP to investigate the use of self-propagating intermetallic reactions for joining the regolith tiles [14]. A mixture of aluminum and nickel was placed into a gap between two tiles and ignited with a CO₂ laser in an argon environment at 10 mbar pressure, leading to a self-sustained propagation of exothermic aluminum-nickel reaction. Figure 2 shows two tiles joined together as a result of this process. The obtained experimental data on the combustion characteristics are in agreement with modeling predictions. Both experimental and modeling results indicate that the quenching distance in the investigated system is small, which implies that a small amount of the reactive mixture would be required for joining regolith tiles on the Moon.

Fig. 2. Two ceramic tiles made of JSC-1A lunar regolith simulant and joined using aluminum–nickel combustion.

Acknowledgments: The author’s research in this area was supported by the National Aeronautics and Space Administration (grants NNX09AV09A and NNX16AT16H). He is grateful to Francisco Álvarez, Sergio Cordova, Armando Delgado, Robert Ferguson, Ashvin Narayana Swamy, and Christopher White for their contributions to this research as well as to Dr. James Mantovani of NASA Kennedy Space Center for his assistance with the fabrication of regolith tiles and helpful discussions.

REVISITING THE RETENTION FRAMEWORK OF LUNAR HELIUM-3 THROUGH SPACE WEATHERING PROCESSES AND ITS IMPLICATIONS. S. Shukla1,2, S. Kumar1 and V. A. Tolpekin2, 1Indian Institute of Remote Sensing, ISRO, India (sshasha@ieee.org, shashi@iirs.gov.in), 2Faculty ITC, University of Twente, The Netherlands (v.a.tolpekin@utwente.nl).

Introduction: The Moon may serve as an expedition base through which human space exploration policies could be strengthened. One of the primary steps to the lunar settlement is the utilization of potential feedstock resources for supporting in-situ operations. $^3$He proves to be an efficient fusion fuel for lunar energy production without any radioactive wastes [1]. The amount of such deposits in the lunar soil is spatially variable, which is highly dependent on the incoming solar wind supply. It is also influenced by the electro-conductive nature of the ilmenite mineral and varying radiation deformities in the crystal lattice [2], [3]. Hence, there is a need to precisely identify such regoliths capable of trapping solar wind $^3$He prior to in-situ exploration. The present study focuses on developing a new spectral parametric framework for lunar $^3$He characterization based on space weathering processes, thereby identifying prospective mining candidates.

Methods: Space weathering influences the regolith in three ways: darkening (albedo, $A$), reddening (continuum slope, $C$), and reduced spectral contrast (integrated band depth ratio, $I$). This study models an improved solar wind plasma fluence ($F$) with the variations in topography and Earth’s magnetotail shielding. The ilmenite abundance ($T$) is further mapped following the Shkuratov’s approach [4]. With increasing maturity, $C$ increases whereas $A$ and $I$ decreases. Such behavior may be attributed to the increase in nanophase iron particles upon reduction of Fe$^{2+}$ during micrometeorite impacts. The solar wind $^3$He retention enhances with comminuted regolith grains, which avails more surface area for the influx. A statistical relationship is, hence, established between 61 in-situ $^3$He estimates and developed space weathering based spectral parameter ($FTC/IA$). Luna samples are included for minimizing saturation effect. Astronaut traverse maps are used to extract the spectral parameters. The preliminary model testing is performed near the Vallis Schröteri region.

Higher Retentivity of Pyroclasts: According to Fig. 1(a), there is a higher correlation of the in-situ records with newly developed hybrid parameter. The measurement bias due to the irregular spatial distribution of samples is minimized by including a site-specific averaging operator. This significantly increases the correlation, thereby exhibiting an error of <1 ppb. The Luna samples receive ~47.77% solar wind flux more than that of the Apollo samples, indicative of higher $^3$He saturation. In Fig. 1(b), the most abundant region tends to be pyroclasts (in red color) with >7.3 ppb and reduced Fe$^{2+}$-band depths. This attributes to highly crystalline regolith gardened with ilmenite-rich glass beads. Further traces of hydrated spectra incline such regions to be of ISRU potential. The site, thus, offers promising exploratory science in terms of evolved volatiles. In addition, the dominating processes affecting the concentration of $^3$He are mainly found to be $C$ and $I$. The developed framework provides new insights into the prospective mining site identification for initiating the establishment of lunar energy sector.

MODELING TOOL FOR LUNAR MINING OPTIMIZATION AND RESOURCE PROCESSING BASED ON GEOLOGICAL CONTEXTS. L. Sibille¹, S. Saydam², C. Tapia Cortez², ¹Southeastern Universities Research Association (SURA), Swamp Works, Exploration & Research Technologies, Mail Code LASSO-013, NASA Kennedy Space Center, FL 32899; email: Laurent.Sibille-1@nasa.gov, ²School of Minerals and Energy Resources Engineering, UNSW-Australia, Sydney, NSW 2052 Australia; email: s.saydam@unsw.edu.au

Introduction: In their assessment of the first Landing Site / Exploration Zone Workshop for Human Missions to the Surface of Mars in Houston, TX, organizers representing NASA’s Science Mission Directorate and Human Exploration Operation Mission Directorate identified the need for a better understanding of the potential resources (reserves) and of the major factors impacting feasibility assessments for extraction on Mars. The participating teams also lacked the tools to analyze the multi-dimensional data sets describing the environmental and geological knowledge of the targeted region and the capabilities of mining and extraction systems.

Today the renewed interest in understanding how access to lunar resources may help pave the path to a cis-lunar economic future forces us to face the same questions: what are the true technical capabilities of the ISRU technologies under development when they face the geological and environmental contexts of the lunar surface? What are the highest priority technology gaps and geological knowledge gaps that impact economic viability of lunar resources exploitation?

ISRU models developed over the years have been particularly valuable in describing the inputs and outputs of regolith processing systems using data collected in field operations by NASA-led teams [1]. At this time, many models often oversimplify the mining and processing systems and do not fully exploit integrated system-level models widely utilized in the terrestrial minerals industry [2]. Other models resort to using overly simplistic descriptions of the geology while high-level economic models of space resource utilization ignore the resource context altogether and use simple parametric scaling laws to describe higher production rates. Altogether, the data output of these tools comes with a high degree of uncertainty.

The work presented here is an effort to augment NASA’s current set of modeling tools with a novel comprehensive mining and materials processing model that integrates the specific geology of the targeted resource, integrating the expertise and best practices of terrestrial mining industries with the knowledge of expert space technologists in ISRU. Results of this work will deliver comparative results on the operations and technologies best suited for a particular resource deposit on a planetary body of choice, based on planetary science data describing the resource.

Space Resources Utilization Simulator: In mining projects, including both terrestrial and off-Earth, there are many variables obtained from diverse sources that interrelated each other. During the planning stage of an operation, if these variables used inappropriately, the consequence could lead technically an unfeasible mine. To avoid this, interactive visual platforms have largely been used in mining industry to facilitate the large amount of data. The main advantage to using these platforms is that their capacity to read and write data from diverse sources and database, and combine all data inputs and settings in a single model for a better mine plan.

Despite geographical and geological differences, most mining operations involve similar tasks that make up a generic model of mining. That model is generally called ‘block model’ which consists of the following tasks: deposit definition (resource/reserve modeling); breaking, extraction and transport of ore and disposal of waste material; processing of ore to yield valuable product and waste tailings; disposal of waste tailings, and transport and sale/use of product. Off-Earth Mining will also have similar tasks; however, the proposed model must identify the required modifications, particularly related to economic value.

This presentation will describe the capabilities of the simulation tool and a case of optimized mining scenario within a geological context.

References:
ADVANCED CONCEPTS FOR MOLTEN REGOLITH ELECTROLYSIS: ONE-STEP OXYGEN AND METALS PRODUCTION ANYWHERE ON THE MOON.

L. Sibille1, S. S. Schreiner2, J. A. Dominguez3, Southeastern Universities Research Association (SURA), Swamp Works, Exploration & Research Technologies, Mail Code LASSO-013, NASA Kennedy Space Center, FL 32899; email: laurent.sibille-1@nasa.gov. 2Jet Propulsion Laboratory, Mail Code JPL:313D, Pasadena, CA 91109; email: samuel.s.schreiner@jpl.nasa.gov, 3Florida Institute of Technology, Melbourne, FL 32901

Introduction: The Molten Regolith Electrolysis (MRE) process has been demonstrated to produce raw feedstock materials and oxygen at high yield with lunar materials under KSC leadership with NASA’s ISRU project funding in the 2000’s [1]. Among current chemical processing techniques, MRE offers the only one-step process to produce oxygen and metals by direct electrochemical separation of molten metal oxides into oxygen and a glassy metallic product collected at opposite electrodes. Melting the regolith rather than involving chemical solvents (an approach used for the terrestrial production of aluminum) simplifies the design, greatly reduces contamination of the produced oxygen and metals, lowers overall landed mass and frees the technology from dependence on consumable components that may not be readily available in space. These attributes and its higher yields of oxygen and metal per unit mass of soil give MRE the edge over techniques requiring chemical compounds to react with mineral constituents. MRE is also the only existing technology to deliver molten metals in their raw form, flowing, moldable and available for processing to become stock for additive manufacturing (3D printing) to enable fabrication and repair techniques for sustained operations on the lunar surface. Previous work on MRE reactors characterized their nominal operations and the electrochemical reactions on which they operate (Sibille, 2009) and showed consistent performance with regolith, even with composition and temperature variations. Though simple in principle, the reaction must occur at a temperature at which the regolith oxide mixture is molten to allow for the movement of newly formed ions toward their respective electrodes. Sustained operation at high temperatures in excess of 1600°C creates a problem for reactor material design both thermally and chemically as molten iron and corrosive oxide melts must be contained. Advances in inert anode material have been made [2, 3] with much work remaining to solve longevity problems in the extremely corrosive conditions at high temperatures, and the inside walls of a reactor remain vulnerable. The solution proposed by Sibille and Sadoway [1] to protect the reactor from this corrosion is a cold-walled reactor design in which the pool of molten regolith is Joule-heated from the inside and the portion directly between the electrodes is molten while the regolith in contact with the inner walls of the reactor remains granular, preventing any contact with corrosive agents. This cold-walled reactor design must include a method to create the molten electrolyte pool exclusively at the center of a regolith bed and thermally manage the system to sustain this configuration. The electrical system must be designed to pass sufficient current to maintain joule heating of the molten regolith. Joule heating relies on the electrical resistivity of the molten oxide pool to produce heat from an electrical current. The material selection for the reactor electrodes are also a subject of ongoing research. At high temperatures, with demanding electrical and mechanical requirements along with the need to withstand extremely corrosive environments from the molten metals as well as the produced oxygen, most metallic materials fail in one of the above areas. The leading candidates for cathode materials are the platinum group metals, and chromium-based alloys which have been studied in extreme environments to varying degrees of success [2, 4]. Despite the many technical challenges it faces, the MRE reactor concept promises extremely high re-wards for its successful development and operation [5]. The oxygen evolved during the MRE process can be easily used in breathable air by astronauts as well as an oxidizer for propellant in launch vehicles.

End-to-End Concepts for Lunar Demonstration: The presentation will highlight a few integrated concepts recently developed by our team to advance this remarkable technology into position for demonstration and testing on the lunar surface. These concepts propose potential solutions for critical operations such as cold-wall reactor start, reactor continuous feed, molten material transfer, oxygen monitoring and process control.

References:

Cryobotics: Testing of Strainwave Gearboxes  J. D. Smith¹, J. M. Schuler², A. J. Nick³, ¹NASA Kennedy Space Center (Mail Code: UB-R1 Kennedy Space Center, Florida 32899, jonathan.d.smith@nasa.gov), ²NASA Kennedy Space Center (Jason.m.schuler@nasa.gov), ³NASA Kennedy Space Center (Andrew.j.nick@nasa.gov).

Introduction: Operating in the extreme Lunar environment has many challenges. One of these challenges includes cryogenic temperature conditions. Realistic performance testing on Earth is essential to designing sustainable hardware for the Lunar surface. Cryobotics is a technology focus area for robotic systems and rotating machinery that must operate at cryogenic temperatures in environments including Earth, low Earth orbit, Mars, Moon, asteroids, Solar orbit, planetary orbit, or those encountered during travel among these destinations. The heat transmission effects of these temperatures, as well as the large temperature differences (ΔT) and quick changes in temperatures (thermal transients), and thermal cycling must be understood by testing in relevant environments. The applications include mining equipment, spacecraft mechanisms, rotating machinery for superconducting power generation, cryofuel pumping systems, and so forth. Participating with science and industry partners in tribology research, dry lube technology, and material science in a collaborative way is a key facet of the focus area of cryobotics.

This abstract addresses the testing of an extreme cold environment test chamber and the initial testing of Harmonic Drive strainwave gear sets and Bulk Metallic Glass flexsplines in strainwave gear sets. This chamber was specifically designed for the testing of actuator subsystems such as planetary gearboxes, strainwave gear sets, and full actuators in vacuum and at approximately 100 kelvin (K) and below. The chamber’s capabilities include life testing while under specific loads, gear efficiency, gear wear, temperature monitoring, and other operational parameters.

The test chamber was verified to accurately measure gearbox performance by testing known COTS gear sets in an ambient temperature and atmosphere environment. Once verified, the chamber was used to test a COTS Harmonic Drive and a Bulk Metallic Glass (BMG) Gear flexspline for a strainwave gear set at less than -200 degree Celsius, in medium vacuum, and a 33 N*m torque was applied. These gear sets were tested without the presence of any grease and were only burnished with moly disulfide.

The results of these tests proved the need more research in this Cryobotics area to advance heater less actuators. The COTS gear set ran without an input load for approximately 5000 input revolutions before failing. Figure 1 shows the flexspline worn teeth after the test was completed. Figure 1. COTS Flexspline after test

The BMG gear set ran without input load for approximately 4500 input revolutions before failing. Figure 2 shows the broken BMG flexspline after the test. Also notice the lack of wear on the teeth.

Figure 2. BMG Flexspline after test

After further examination of the gear teeth wear and data crunching it seems that even though the BMG gear set failed before the COTS gear set, it may have performed better if it did not have a stress concentration from a manufacturing defect that caused it to shear the flexspline below the teeth. Future work will correct this manufacturing defect to continue the testing of strainwave and planetary gear sets and full actuator systems.
Due to the rotation around the axis, temperature on the Moon surface varies from 100 to 390 K (-173°C to +117°C). In the constantly shaded depressions in polar regions, its value decreases to 50 K [2, 8–10]. At such conditions, it is necessary to create specific protection against temperature and powerful solar radiation. Therefore, it is clear that on the Moon a person can live on the surface only in shelters with powerful walls, or below the surface [1, 3]. To do this, arriving on the surface of our satellite, a person must first of all protect himself from extreme temperature and radiation. In our opinion, the most appropriate way is to place astronauts under the surface of the moon [6]. To this end, it is necessary to develop a technology for the very rapid construction of residential and industrial premises and their heating systems there. Heat penetrates deep into the soil due to thermal conductivity [6, 7]. But the thermal conductivity of the lunar regolith is very low. For example, almost 230 years ago, the French scientist A.L. Lavoisier proved the year-round constancy of temperature at + 11.7°C at a depth of 28 meters in the Paris Observatory. For Kiev, such a constant temperature is always + 9°C. At the beginning of the twentieth century mathematician Steklov A.L. has solved the problem of mathematical physics for the thermal conductivity of a semi-infinite rod. This solution could explain such planetary phenomena. Solving a similar problem for the Moon, using the temperature difference in the equatorial part of its surface in the range from + 117°C to -173°C, we found that the temperature difference below the surface at depths of 1.5 to 20 meters will be constant too.

And under the surface (endo) of the Moon, this constant temperature depending on the latitude will be from -20 to -50°C. That is why the Main Astronomical Observatory of the National Academy of Sciences of Ukraine is working on the topic “Thermal systems for terraforming of planets and planetoids.” The authors have developed an effective technology for creating special daytime light “wells” to heat the ground by sunlight near the settlements under the lunar surface. To transfer energy from the Sun to subsurface rooms we offer lift up at the morning periscope of lens-mirror coelostat installation. Such installations can work the whole lunar day, tracking the movement of the Sun across the sky, and to redirect beams of light to special accumulating systems, that are located below the surface. This will allow the formation of special “heat accumulators” around and above our “endosettlements”. With the onset of the evening, the retractable parts of the periscope with coelostat must be omitted in wells under the surface; and immediately these wells must be closed for the night by powerful covers of thermal insulation material. This will provide at night a comfortable temperature (+15±25°C) for the biological form of life. After 15 Earth days the built-in periscope is again will be brought to the working position.

And the area to accommodate such endosettlements on the moon is millions of square kilometers! It remains to provide them with water and special spacesuits for long-term residence and the extraction of resources of our satellite [4, 5, 11-13]. Therefore, we must first send to the Moon special robots-builders and/or specialized 3-D printers for carrying building works. Initially, special symbiotical cocoons for long-term endostation stations can be placed in small shallow craters and covered with a nearby layer of regolith. Here we must build a network of solar power plants too.

We believe that researchers need to pay particular attention to the analysis of the above information. Continuing research in this direction will be very interesting and promising.

Methods of heating areas for human living under the surface of the Moon. A. F. Steklov\textsuperscript{1,2}, A.P. Vیدmachenko\textsuperscript{1,3} and D.M. Miniaylo\textsuperscript{1}, \textsuperscript{1}Interregional Academy of Personnel Management, Str. Fromtevskaya, 2, Kyiv, 03039, \textsuperscript{2}Main Astronomical Observatory of the National Academy of Sciences of Ukraine, Str. Oh Zabolotnogo, 27, Kyiv, 03143, \textsuperscript{3}National University of Life and Environmental Sciences of Ukraine, St. Heroyiv Oborony, 12, Kyiv, 03041, stec36@i.ua.

The temperature on the Moon's surface at the equator varies from -173°C to 117°C. At 1 m\textsuperscript{2} of the surface of the moon from the Sun comes more than 1.3 kW of energy. This energy must be taken\cite{1, 3}, transformed, transmitted under the surface of the satellite, there accumulated\cite{4, 5} and then to be used for everyday needs and for heating of habitations\cite{2}. The energy brought from the Sun must be collected by solar collectors on the carrier heat substance. In practice, such carrier can be oil oils, glycerol, freon, nitrogen, metal melts (Sn, Pb, Na, K), etc.

The outer part of the heat pipe should be transparent, and on its inner part should be applied absorbing solar energy coating, covered with black paint, black nickel, spray titanium oxide and connect with the heat conducting system. The heated carrier heat substance, circulating through the collector, will transmit heat energy to the tank-accumulator, where a hot coolant of another type will accumulate. Getting high operating temperatures can be achieved by controlling of heliostats on two coordinates; or should use parabolic cylindrical mirror concentrators with a heat carrier placed in the parabola focus in the receiving heating tank.

Such systems can be up to several tens of meters long and up to 2-3 m high. Such mirrors should be oriented along the meridian on the surface of our satellite, set in rows on a few meters away and monitor the position of the Sun, turning the mirrors around the "south-north" axis. Since solar collectors work only during the daytime, to save heat in heat supply systems, you need to have special devices that can accumulate heat and then give it as much as you need. Such systems are called thermal accumulators.

Heat can accumulate in a material with a high heat capacity (magnesite, cast iron, high-strength brick, eutectic mixtures of alkali metals, crystals of inorganic salts, etc.) Also, thermal accumulators can be covered with a material with high thermal insulation properties for storage under the Moon's surface of the hot heat carrier.

For efficient operation, the volume of the heat accumulator should be large enough to accumulate the required amount of thermal energy. In addition, such a buffer tank also increases the inertia of the heating system.

Introduction: A solar power infrastructure around Shackleton Crater (SC), at the South Pole of the Moon, would leverage the favorable conditions of sunlight in the area [1] and power multiple assets simultaneously and without interruptions. The concept has evolved from a study funded by the NASA Innovative Advanced Concept (NIAC) Program, in which the main idea was to put heliostat reflectors on the rim of SC to redirect sunlight into areas of darkness inside or outside the crater, creating oases of energy.

Placement of the reflectors: An optimization program is run to determine the best placement in surface coordinates and in height above ground, for a given number of reflectors. The reflectors are to be placed such that they are complementary in function, and at least one reflector sees the sun at least in part above the horizon, and also has direct line of sight to the region where solar energy needs to be reflected. Without loss of generality the study focuses on reflecting the solar power directly; however conversion and transmission by microwave or laser is also considered. The location and corresponding oasis map for three reflectors placed 300 meters above ground level are shown in Figure 1 [2].

Figure 1. Locations of set of three reflectors and oasis region receiving 99% annual sunlight.

The annual illumination percentage as a function of the height of the reflectors above the ground, on the crater rim, is shown in Figure 2.

Sizing reflectors for obtaining LH₂/LO₂ propellant: An architecture for sustainable human exploration of Mars enabled by water from the lunar poles was presented in [3]. The architecture would be enabled by 7.5 metric tons (t) of propellant per day, hence 10 t of ISRU extracted water.

Figure 2. Annual illumination percentage vs height of reflectors placed at locations in Figure 1.

An estimated ~0.6 MW thermal power (assuming 10% water in regolith), and, in a lossless transmission, ~0.6 MW solar power needs to be reflected from the rim. About 2 MW electric power, which may add to 6 MW of solar power reflected, would be needed for obtaining LH₂ and LO₂.

Implications for a lunar economy: The solar power could be reflected or concerted and then transmitted via laser or microwave; tradeoffs depend on distance and end use. Final destination could be reached via multi-hop relays, in a network that could extend tens of kilometers from the south pole (or north pole). Such an energy infrastructure would be an enabler for lowering cost of operations and stimulating a lunar economy. The energy infrastructure would to a large extent eliminate the extreme environment barrier: cheaper solar-powered robotic systems built for Earth-like conditions can be sent in long duration missions. It would modify the business practice as missions will only pay for thermal and energy after confirmed safe arrival landing and money will be paid in increments as opposed to upfront. Such an infrastructure could change the way missions are designed and operated, lower the barriers of entry for new participants in lunar exploration and economy, would allow long term missions in regions without natural solar illumination.

LUNAR TETHERED RESOURCE EXPLORER (LUNAR T-REx): IDENTIFYING RESOURCES ON THE MOON USING TETHERED SMALLSATS. T. J. Stubbs1, M. E. Purucker2, J. D. Hudeck2, R. P. Hoyt3, B. K. Malphrus4, M. A. Mesarch1, M. Bakhtiari-nejad1, G. E. Cruz-Ortiz1, E. T. Stoneking1, T. E. Johnson2, D. J. Chai1, D. C. Folt1, and R. R. Vondrak1, 1NASA Goddard Space Flight Center, 2NASA Wallops Flight Facility, 3Tethers Unlimited, Inc., 4Morehead State University. Point of contact: Timothy.J.Stubbs@NASA.gov

Introduction: On Earth, economically viable mineralization associated with large impact craters can often be identified by its magnetic signatures [1,2]. The magnetic field from these features decays with the inverse of distance, such that identification requires low altitude measurements. On the Moon, many of the large Nectarian-aged impact features have prominent magnetic features associated with their central peak regions [3]. It is possible that the signatures of economic mineralization could be identified at the Moon with low altitude (<20 km) in situ magnetic field measurements.

Tethered Architecture: However, low altitude lunar orbits (~50 km) tend to be unstable, such that without regular orbit maintenance maneuvers they last only a few weeks before impacting the Moon [4]. A mission surveying lunar magnetic fields would require at least a few months, if not more than a year. The fuel mass burden for maintaining a low altitude orbit is prohibitive, especially for SmallSats. The Lunar Tethered Resource Explorer (Lunar T-REx) team is studying the possibility of using two SmallSat/CubeSat buses connected by a tether that is many kilometers in length, such that they orbit in a gravity gradient formation (see Figure 1). The main advantages over a more conventional mission architecture are that low altitude measurements can be achieved with a much longer mission lifetime.

Payload and Measurements: The primary payload on each spacecraft would be a mini-magnetometer deployed on a stacer boom. The dual-point (high and low altitude) measurements would enable a more accurate determination of the lunar magnetic fields. Also included would be nadir-facing, mini-cameras to image surface features for more accurate registration (lower spacecraft), and monitoring tether deployment and dynamics (upper spacecraft).

In addition to identifying the magnetic signatures of potential resources, the measurements would address science objectives identified in the 2014 NASA Science Plan, Planetary Decadal Survey, as well as Strategic Knowledge Gaps (SKGs).

Leveraging: Lunar T-REx builds upon the findings of the Bi-sat Observations of the Atmosphere above Swirls (BOLAS) concept study funded by the Planetary Science Deep Space SmallSat Studies (PSDS3) program [6,7]. The primary BOLAS target was the Gerasimovich crustal magnetic field and

Figure 1: A tethered lunar CubeSat mission.

swirls. BOLAS consisted of two EPSA-class SmallSat connected by a 25 km tether with the formation center-of-mass in a “frozen” orbit, which was stable for at least a year and had a 30° inclination. At closest approach, the lower spacecraft (BOLAS-L) was only 2 km from the surface, and regularly surveyed Gerasimovich at altitudes <12 km.

In turn, BOLAS leveraged on-going experience from the Lunar IceCube mission being developed for EM-1 (PI B. Malphrus), as well as heritage from tethered missions that had flown in low Earth orbit [8].

The BOLAS concept was shown to be feasible, with the next steps being: (i) maturation of the tether deployment system for a lunar application, (ii) assessment of tether survivability against dust impacts in lunar orbit, and (iii) development of an attitude control system (ACS) model that could account for tether forces. These modest investments would advance the “game-changing” technology required for realizing tethered missions to the Moon with a wide variety of applications.

XTRA: AN EXTRATERRESTRIAL REGOLITH ANALYZER FOR RESOURCE EXPLORATION. G.J. Taylor1, D.F. Blake2, T.F. Bristow1, J. Chen1, P. Dera1, R. Downs3, M. Gaillanou4, P. Lucey1, W. McKenzie1, L. Martel1, R. Quinn1, P. Sarrazin6, K. Thompson4, R. Walroth1 and K. Zacny7 1Univ. of Hawai‘i Honolulu, HI (gtaylor@higp.hawaii.edu), 2Exobiology Branch, MS 239-4, NASA Ames Research Center, Moffett Field, CA 94035 (david.blake@nasa.gov), 3Baja Technology LLC, Tempe, AZ, 4Univ. of Arizona, Tucson, AZ, 5IM2NP-Aix Marseille Universite’-CNRS, 6SETI Institute, Mountain View, CA, 7Honeybee Robotics, Pasadena, CA.

The importance of mineralogy to lunar science and exploration: The mineralogical composition of lunar soil can be used to elucidate its petrogenesis and that of its parental rock types, as well as subsequent metamorphic events. In addition to its value to landed lunar science and as ground truth for orbital missions, in-situ mineralogical analysis can be used to evaluate potential In Situ Resource Utilization (ISRU) processes such as the extraction of water or oxygen, metals (e.g., Fe, Ti, or Al), or of ceramic (sintered) building materials. Mineralogical analysis can be used to discover ore deposits useful for extraction, such as rare earth elements, U, and Th (e.g., phosphate minerals, zircon).

Mineralogical analysis using X-ray Diffraction and X-ray Fluorescence (XRD/XRF): XRD is the only in-situ technique able to definitively identify, quantify and determine the elemental composition of minerals present in lunar regolith. XRD can also determine the quantity of X-ray amorphous material present in a regolith sample, and when combined with XRF, the elemental composition of the amorphous component(s). Taken together, these techniques provide a comprehensive analysis of lunar regolith mineralogy that can only be improved upon by sample return. Taylor et al. [1] report the mineralogy of 118 returned Apollo regolith samples in the <150 μm grain size range analyzed by Terra, a commercialized version of the CheMin instrument on the Curiosity rover on Mars. Fig. 1 shows example results from an ISRU test during the 2007 Scarab-RESOLVE field demonstration [2]. XRD patterns and mineral abundances from [1] are available on the Open Data Repository https://odr.io/lunar-regolith-xrd.

The eXtraTerrestrial Regolith Analyzer (XTRA): XTRA is an X-ray Diffraction / X-ray Fluorescence (XRD/XRF) instrument capable of quantitative analysis of as-received lunar regolith when deployed from a small lander or rover. XTRA is a CheMin inspired XRD/XRF instrument with enhanced XRF capabilities (11<Z<30) due the incorporation of a Silicon Drift Diode (SDD) detector in reflection geometry, as well as its operation in vacuum at the lunar surface. As-received regolith samples are delivered to the XTRA instrument and placed in a vibrated, reflection geometry cell. Collimated X-rays from a Co anode X-ray tube intersect the sample surface at an acute angle. Diffracted CoKα photons between 15–60° 2θ are detected by an energy-discriminating, single photon counting CCD. These photons are identified by their energy and summed into a 2D array that constitutes the diffraction pattern of the sample. A histogram of the energies of all photons detected by the SDD detector constitutes an X-ray fluorescence spectrum of the sample. Fig. 2 shows the geometry of the XTRA XRD/XRF experiment and its expected products.

LUNAR LAVA TUBES AS POTENTIAL SITES FOR HUMAN HABITATION AND RESOURCE EXTRACTION. L. W. Tombrowski and A. A. Mardon, Antarctic Institute of Canada (Post Office Box 1223, Station Main, Edmonton, Alberta, Canada T5B 2W4, aamardon@yahoo.ca).

Introduction: It has been suggested in the past that potential manned missions to the Moon could make use of lunar lava tubes as habitable shelters and/or storage areas. These tubes could provide protection against cosmic radiation, micrometeoroids, meteorites, and other natural hazards while also providing a habitable environment with relatively stable temperatures compared to the wildly fluctuating day/night temperatures on the Moon’s surface.

Benefits: Building a manned lunar base inside of a lava tube has many potential benefits. The temperature inside of the tubes is relatively stable, so space suits and base modules would not require as extensive of temperature regulation systems as on the surface of the moon. This would allow astronauts a greater degree of freedom of movement while inside the tube. Eliminating the need for bulky insulation also means a lunar base only requires pressurization, therefore improving the size and portability of base components. This, however, assumes that the risk of debris falling from the roof of the tube is negligible. The protection from cosmic radiation inside the tubes presents the possibility of a long-term manned lunar mission without the need for as extensive of shielding from radiation. Building a base beneath the Moon’s surface also provides the opportunity for mining operations and geological study.

Further Study: More information on the exact location, structure, and depth of lunar lava tubes is required. At the present moment, only observational evidence has been found to support the existence of lava tubes on the Moon, such as entrances to tubes on the surface and signs of possible collapsed lava tubes. Unmanned missions using lunar rovers and/or probes must be conducted in advance of a manned mission in order to determine the suitability of a tube for human habitation and resource extraction. Safe and efficient methods of moving supplies, astronauts, other equipment, and any potential resources extracted from the tube in and out of the tube must also be researched. Due to a lower gravity and absence of atmosphere, lunar lava tubes could be significantly larger than lava tubes on Earth.

Seismic Activity: The exact cause and intensity of seismic activity on the moon is currently unknown. Therefore, more study on the seismology of the Moon must be conducted in order to measure the potential risk of a lava tube collapsing or debris falling from the ceiling of a tube. Methods for safely clearing the floor of a tube of debris, boulders, or other potential obstructions must also be looked into.

Power: Considering the scenario where the main base and living quarters are located inside of a lunar lava tube, options for the storage and generation of power must be examined. If the power is generated from outside the tube (i.e. solar panels), an appropriate power transfer system and backup system must be established inside the tube, or vice versa if power is generated inside the tube.

Conclusion: The usage of lunar lava tubes for human habitation, storage, and/or resource extraction in future missions to the Moon is largely theoretical at this point in time. There are unquestionably great potential benefits to the concept, however a considerable amount of study and further unmanned missions to the Moon will be required before any conclusions regarding the viability of the tubes can be reached.

**Regolith Size Sorter and Hopper**

1NASA Kennedy Space Center – Granular Mechanics and Regolith Operations Laboratory
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**Introduction:** Regolith derived resources are required to support a future Lunar economy. These resources are needed for many applications for example: water extraction, oxygen extraction, and construction. These applications require size sorting of the regolith to operate or increase efficiency. Each application requires different particle size distributions. KSC developed a hopper which implements size sorting and transfer of regolith. The regolith size sorter and hopper investigates incorporating size sorting techniques, which are currently used in industry. A prototype unit was built and tested. The size sorting techniques included grizzly bars and a trommel. The grizzly bars work as a first step to block particles with a size above the spacing of the bars. The regolith remaining after the grizzly bars is deposited into a hopper with an internal aguer. The auger conveys material to a trommel, which has a rotating screen. The screen hole size determines what size particles get sorted. The trommel has two exits: particles which fall through the screen and particles which fall out the end. Both material exits can be used as the primary sorted material depending on the required material size. A multistage trommel can be used to further sort particles to a specific particle size distribution.
Development of the PROSPECT Payload Package for Subsurface Sample Acquisition and Analysis of Lunar Volatiles. R. Trautner\textsuperscript{1}, S. J. Barber\textsuperscript{2}, J. Carpenter\textsuperscript{1}, R. Fisackerly\textsuperscript{1}, B. Houdou\textsuperscript{1}, M. Leese\textsuperscript{2}, A. Rusconi\textsuperscript{3}, E. Sefton-Nash\textsuperscript{1}, A. Zamboni\textsuperscript{3}, \textsuperscript{1}European Space Agency, ESA/ESTEC, Keplerlaan 1, 2200AG Noordwijk, The Netherlands, Roland.Trautner@esa.int, \textsuperscript{2}School of Physical Sciences, The Open University, Milton Keynes, MK7 6AA, United Kingdom, \textsuperscript{3}Leonardo SPA, Airborne & Space Systems Division, Viale Europa s.n.c. (MI), Nerviano, Italy.

Introduction: PROSPECT is a novel payload package for in-situ exploration of lunar resources, with a focus on volatiles. As part of the new Russian Lunar Exploration Programme [1], the Russian Luna-27 spacecraft (Luna-Resource lander) is scheduled to land in the lunar south pole region in 2023. Among its payloads, it will carry a complex package called PROSPECT [2] provided by the European Space Agency which will support the extraction and analysis of lunar surface and subsurface samples as well as acquisition of data from additional environmental sensors. The key elements of PROSPECT are the ProSEED drill and the ProSPA analytical laboratory. ProSEED will enable the acquisition of samples from depths of ca. 1m and deliver them either to ProSPA or to Russian instruments. ProSPA will receive samples, seal them in miniaturized ovens, and process them via heating, physical and chemical processing of released volatiles, and analysis of the obtained constituents via mass spectrometry. Additional sensors are foreseen to provide contextual information, such as cameras for the acquisition of multi-spectral images of drill working area and acquired samples, as well as temperature sensors and a permittivity sensor that are integrated in the drill rod. A Central Electronics Unit (CEU) provides control and data management for the drill, and also manages sensors as well as the ProSPA instrument operations. PROSPECT is a modular system with high re-use potential on subsystem and subassembly level, with flight hardware expected to be available in 2021 for contribution to a variety of lunar platforms including landers, rovers and surface-deployed packages.

In early 2019, the project will transition into Phase C, and proceed towards its Critical Design Review.

In our paper, we will present the PROSPECT design and expected drill, instrument and sensor performances. Re-usable elements will be highlighted, and a project status update will be provided.

ROBUST ELECTROLYZER FOR LUNAR ISRU APPLICATIONS. R. C. Utz, M. C. Miller, S. Pass, and Thomas I. Valdez, Teledyne Energy Systems Inc. (10707 Gilroy Road, Hunt Valley, MD 21031) thomas.i.valdez@teledyne.com

Introduction: The National Aeronautics and Space Administration (NASA) is seeking industry support to develop a pathway for human spaceflight into cis-Lunar space and for the habitation of planetary bodies. NASA is specifically working towards the capability to sustainably live beyond the Earth [1]. In-situ resource utilization (ISRU), the production of mission critical consumables on planetary bodies used for human exploration that would otherwise be brought from Earth, has been identified by NASA as an exploration element that has no flight precedent. Teledyne Energy Systems Inc. (TESI) is developing a robust electrolyzer for Lunar ISRU Applications. The TESI ISRU electrolyzer is intended to support the generation of hydrogen and oxygen from ice mined from the Moon.

Discussion: Research on electrolyzers for use in space applications has primarily focused on the development of proton exchange membrane (PEM) technology. PEM-based electrolyzers will not have acceptable durability without a robust water di-ionization system when being fed water from ice mined on the Moon. A water processing subsystem to remove ion contaminants from the ISRU water feed stock will require maintenance that may add complexity and thus lower system reliability [2]. The TESI ISRU electrolyzer is based on a cation exchange membrane that is robust to contaminants found in Lunar regolith. During oxygen generation, a solution of Lunar regolith infused water (testing will occur with a Lunar regolith simulant) is introduced to the anode compartment of the TESI ISRU electrolyzer and is electrochemically oxidized to oxygen gas, water, and sodium ions as power is driven into the electrolyzer. The sodium ions are then conducted across a cation conducting membrane to the cathode. At the cathode, the sodium ions electrochemically reduce water to form sodium hydroxide and hydrogen gas. A functional schematic of the TESI ISRU electrolyzer is shown as Figure 1. The anode and cathode catalysts of the TESI ISRU electrolyzer consist of nickel-alloy catalyst. This system is inherently robust to the contaminants found in ice mined from the Moon. The electrolyzer is operated in a dual irrigious (dual-feed/ flooded) configuration to maximize oxygen production.

Figure 1: Functional schematic of the TESI ISRU electrolyzer.

It is anticipated that the TESI ISRU electrolyzer will produce 1.1 kg of oxygen per hour when fed 6.7 kW of electrical power. The goal for the electrolyzer performance is to meet a metric of 5.6 W/(kg O2/hr) while operating on a simulated Lunar ISRU water feed stock.

Conclusion: This paper will review the advantages of the TESI ISRU electrolyzer versus state-of-the-art technology. Special attention will be given to understanding electrolyzer failure mechanisms with respect to contaminants that can be found in Lunar regolith. The design, development and testing of the TESI ISRU electrolyzer will be discussed. The ISRU community will be apprised of an ISRU design concept for the production of hydrogen and oxygen reactants.

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References:

PROPOSED NEW TESTING FACILITY FOR COLD AND OPERATIONAL LONG DURATION TESTING OF LUNAR AND MARS ISRU AND MOBILITY. P. J. van Susante¹ and R. Alger², ¹Michigan Technological University, Dept. of Mechanical Engineering – Engineering Mechanics, 1400 Townsend Drive, Houghton, MI 49931, pjvansus@mtu.edu, ²Michigan Technological University, Keweenaw Research Center 116, rgalger@mtu.edu.

Introduction: The current and future plans for mining water and other resources from the Moon, Mars and asteroids will require development and testing of space mining equipment. Initially missions for identification and characterization of resources will be flown and brought to the lunar surface on a variety of platforms such as supported by the NASA CLPS program. Mining equipment to excavate, comminute, transport, transfer, process and store resources will need to be developed and tested under relevant conditions. Initially laboratory and small scale short duration vacuum tests will be sufficient for identification and characterization missions but actual mining and production equipment will be larger due to desired production rates and have to function for years with minimal (if any) maintenance and supervision. Reliability, wear and tear, mobility, autonomy, long term dust effects and regolith mechanics will all need to be studied at scale and under relevant conditions. NASA and other organizations have (large) vacuum chambers to do short (and some long) duration tests but most do not allow regolith simulants to be used in them for testing. Analog sites are great for testing operations in the field and with similar landscapes but are often extremely remote and far from infrastructure necessitating short duration campaigns and challenges with support such as high bandwidth communication, logistics, etc. No facilities currently exist that can handle the requirements for the testing of full size ISRU equipment and for required durations under relevant conditions. We propose to develop a test facility as part of Michigan Technological Universities (MTU) Keweenaw Research Center (KRC) to allow for large scale, long duration ISRU and other testing under simulated Lunar and Martian conditions including regolith simulants, ice-content, lighting, temperature, terrain and duration.

Existing Facility: MTU has an existing 900-acre research facility, KRC, designed for mobility testing under extreme terrain and temperature conditions. This facility is used for cold weather testing by all large car companies, the US Army Tank Automotive Research Development and Engineering Center (TARDEC), the US Army Cold Regions Research Engineering Lab (CRREL) and many others for automotive and robotics long duration and unstructured environment performance research. The test tracks and terrain have been fully digitized in a virtual environment so simulations of expected performance can be compared to actual performance in the field. Excellent high bandwidth data connections are present and the facility is located next to the local airport. The test facility (layout shown in figure below) consists of 900 acres of test terrain that contains a basalt quarry where basalt can be crushed at large scale to the particle sizes and distributions required, winter test tracks and facilities, many different (customizable) terrains, slopes and surface features as 30x40ft bays that can cold soak vehicles to -40°C. In addition, the area has large basalt lava flows (hundreds of basalt flows including one of the world’s largest lava flows by volume, 1650 km3 are located here [1]) and acres of leftover stamp-sands (crushed basalt rock from stamp mills) that can be adapted for trafficability simulants and field testing of ice concentration and variability detection. We are looking to collaborate with the Lunar and Mars ISRU community to provide inputs to the study to use KRC as a full-scale long-duration ISRU testbed. Also of interest is the ice/water content developed in the granular materials during initial frosts and thaw during spring time. These deposits could serve as analogs for field test sensors, trafficability, and extraction hardware in a mix of granular crushed basalt materials with varying ice contents that are easily accessible.

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A MODULAR ROBOTIC SYSTEM FOR IN-SITU EXTRACTION AND PROCESSING OF LUNAR RESOURCES. L. A. Vaughn, Triplanetary Exploration Systems, Inc. tony.vaughn@triplanetary.space.

Introduction: It is expected that the next decade, and the decades to follow will see increasing scientific, commercial and industrial activities on the Moon, ultimately including human colonization. In order to support these activities without importing impractical amounts of mass from the Earth, resources originating on the Moon will be utilized as raw materials in the construction of habitats, manufacturing of fuel, growing of food and a wide range of related activities. This paper discusses some of the requirements and solutions that can be tested in a demonstration system as part of a prospective future mission concept.

Discussion: A mining and manufacturing facility on the Moon will of necessity have a layout that divides certain activities into logical parcels around the region where the facility is located. Input materials for processing can include lunar fines and larger gravel in the regolith, and even stones and boulders that are distributed around the region. While resources can be collected ad hoc for a small operation, a full scale facility will have one or more areas designated for excavation of source materials. Another area will be designated for materials processing. Again, in a small demonstration mission all the materials processing activities might be conducted in a plant that is kept onboard a lander, but in a larger operation there might be several distinct processing plants that are brought by a landing craft and relocated to designated places in the worksite. For large-scale operations, there would need to be allocation for stockpiling of input, intermediate, and final materials. These areas should be located at some distance from a landing pad in order to protect them from debris generated by rockets on landing and take-off. Finally, if construction activities are to take place at the same location as the mining operation, there will be another area designated for that.

In a functioning facility of this type, materials will need to be moved regularly between the different parcels as they flow between excavation, processing, storage, and preparation for transportation to the end customer, or utilization on site. This paper proposes a modular, multi-functional design for a system of robotic components that can perform all the required tasks of collection and movement with a minimum of complexity and provide for repair of defective systems by swapping spares.

References:
MINERALOGY OF MOON SURFACE AT REMOTE POLARIMETRIC INVESTIGATIONS. A. P. Vidmachenko1,2 and A. V. Morozhenko1, 1Main Astronomical Observatory of National Academy of Sciences of Ukraine, Str. Ak. Zabolotnogo, 27, Kyiv, 03143, 2National University of Life and Environmental Sciences of Ukraine, St. Heroyiv Oborony, 12, Kyiv, 03041, vida@mao.kiev.ua.

Moon has a rich base of raw materials with the potential use of these materials to facilitate human activities on our satellite and the use of resources for the development of world industry. From the point of view of the resource, the deposits of volcanic pyroclastic deposits formed during volcanic eruptions are especially interesting [20]. At orbital remote observations of such deposits it was found > 100, and 12% of them have an area > 1000 km2.

The current problem at studies of the Moon is still the mineralogical mapping of its surface [8, 9, 17-19]. Since it is not yet feasible to build such maps based on data from contact methods of research, the need to develop reliable remote methods has emerged. This can be done from the space aparat in the polar orbit of the Moon [13, 15, 16]. Such a polar satellite can be equipped with devices, experience of developing and manufacturing of which - have an Ukrainian scientists. 1) A camera with selected filters to produce images with the required resolution [2]. 2) Spectropolarimeter for determining some physical soil parameters [3-7]. 3) Spectrometer for spectral range which covering the strips of pyroxene. Due to the absence of the atmosphere and clouds on the Moon, observation of its surface can be practically continuous.

We propose to employ an experiment of polarization mapping of the surface of the moon at a wavelength of 240-290 nm within the phase angles of 80-120°. To do this, according to the values of the phase angle, which has the maximum value of the degree of polarization (Brewster angle), the value of the actual part of the refractive index of the substance should be determined [10, 14, 21, 22]. To minimize the effects of multiple scattering, which values of this angle are "smeared" in a certain range of phase angles Δα, we propose to use observation in the ultraviolet region of the spectrum, which has an extremely low reflectivity of the soil (at the level of 1-2%), and therefore the effects of multiple Scattering is reduced to practically zero. Therefore, in this spectral diapason, the value of the Brewster angle [17] is more clearly defined.

That is, we propose mapping the values of the real part of refractive index with the analysis of the empirical relation between the maximum value of the degree of linear polarization and the normal albedo, taking into account the contribution of a one-time Fresnel reflection. We can also use the spectral values of the second Stokes parameter. Its advantage is the practical absence of multiple scattering effects.

We also continue to develop and manufacture original spectropolarimetric devices [1, 11, 12] that we can use for ground support of both Ukrainian and international space missions to the Moon.

Introduction:
With the current direction of missions and focus of research, the need for development of new approaches to characterization of sediments and creating a more interdisciplinary research environment for the samples gained is clear. Currently there is little in the way of a detailed strategy for identification, characterization and processing of lunar resources. Given the aggressive timelines of the planned campaign, a wider range of academic expertise in earth-sciences from a range of disciplines could heavily influence the realistic research scope for missions. A critical part of the plan of expansion to space includes the increased research scope of lunar resources, as an enabler for long term habitation and as the first steps towards the goal of establishing a thriving, sustainable cislunar economy.

The expansion of research expertise applied to the borehole cores gathered will enhance understanding and promote space research as a wider field of research. Data gathered by the Clementine, Lunar Prospector, SELENE, Chandrayaan-1, LRO, LCROSS, and other missions have shown there are potential mineral and volatile resources on the Moon that could be used to sustain human life on the lunar surface and to develop a transportation architecture for human spaceflight beyond the Earth-Moon system. Utilization of these resources requires detailed assessment techniques. Given recent findings of up to 30 wt.% water ice in some permanently shadowed regions at the poles of the Moon (Li et al., 2018), the time is now right to develop a phased approach to start to develop these and other resources, as proposed in the LEAG Lunar Exploration Roadmap Implementation Plan, NASA’s ISRU Roadmap, and the latest version of the Global Exploration Roadmap ISRU Strategy.

The research proposed is to create an interdisciplinary Sample Testing Framework for Space Utilization, combining earth sciences with current astrobiology testing. This would be done using the newly developed Sample Testing Framework for Undisturbed and Disturbed borehole samples developed by PhD student Frida Klabo Vonstad at University College London (UCL) in Civil, Environmental & Geomatic Engineering.

The conceptual Sample Testing Framework which shows how an interdisciplinary collaborative approach can help disciplines work in a synergistic manner, and enables the research of similar interdisciplinary collaborations in the future in various earth-research fields. The research is currently being tested for applications in industry and academia, to reduce risk on construction sites, save cost and time, and to create more efficient work practices. The research will attempt to adjust the Framework to suit the need of lunar and martian core samples for synergistic interdisciplinary testing.

References:
Introduction: In order to enable operations and long-term human and robotic presence on the lunar surface, our ISRU Synthesis work advances the science and technology required for scalable production of locally-sourced building materials as well as propellants and volatile products from raw lunar feedstocks. The goals of this work are: 1) to study the feasibility and scalability of additive manufacturing (AM) at various locations on the lunar surface; 2) the production of volatile products; 3) the advancement of ISRU 3D printing and heat-print-release capture (HPRC) cryotrap technology; and 4) the operational demonstrations of developed hardware under environmental conditions. We specifically target the following investigations: (i) plasma synthesis of propellants and cohesive polymer binders from lunar volatiles; (ii) additive manufacturing methods of sintered, molten, and polymer-bonded regolith structures; (iii) characterize material and mechanical properties of the end products; (iv) characterize radiation and heat shielding properties of bricks for astronaut shielding.

Production of Fuels and Polymers: A component of a solid rocket propellant composed of an extended heterocyclic structure can be synthesized via reactive plasma processes, starting from carbon monoxide as a low-cost gaseous feedstock (Figure 1). Here at SwRI we will assess what reaction pathways can lead to the synthesis of useful products that can be efficiently accessed from the available volatile species on the Moon and then synthesize key chemical intermediates, gas-phase oxygen, synfuels, solid propellants, and polymers from reactive plasma processes based on RF and high-power DC impulse excitation.

Additive Manufacturing on the Lunar Surface: We are starting a detailed investigation into two AM methods, designing a new type of AM volatile capture system and advancing its TRL, as well as build an environmental chamber to test and host ISRU technology demonstrations of the HPRC, AM, and numerous hardware modules emerging from other ISRU research conducted. We’ll explore magnetic induction and polymer binders, as well as microwave sintering with our Korean collaborators. They will utilize nanophase iron in their simulant KLS-1. Nanophase iron drastically increases the effectiveness of microwave sintering, previous work has been lacking in this critical element of thermal sintering catalyst. Additive construction by cohesive binders offers an enticing alternative to sintering or molten extrusion, especially if the binders can be produced in-situ from excavated volatiles, therefore we are working on the development of highly ordered polymers in structured materials, and the application of these polymers as binders to strengthen and mold lunar regolith.

Magnetic induction (MI) heating, which can save on cost and power, heats conductive metals through heat generated in the feedstock by eddy currents. We have partnered with RedWorks, LLC and are currently utilizing their (TRL 3) 3D print system (Figure 2) to explore lunar ISRU applications, including radiation shielding to protect astronauts.

The energy inputs for ISRU and AM on the lunar surface may require robust and efficient power systems, but the combination of the synergistic ISRU subsystems can be intertwined to save substantial energy savings. RedWorks’ 3D print head will be modified to capture off-gassing volatiles and cold trap them in in the HPRC system. A HV chamber will capture the sublimating volatiles in a cryo-cooled cold trap released from lunar regolith simulants such as H2O, CO, H2S, NH3, O2, SO2, CO2, and H2 (Figure 3).
Greenhouses as the Source of Rare Lunar Resources.
Dr. John M Wilkes , Retired Professor of STS (Science, Technology and Society Studies) and Sociologist, Worces-
ter Polytechnic Institute, Worcester, MA 01609 [jmwilkes48@gmail.com]

In 2010 I led a team that designed a second gen-
eration lunar base (after the man in a can camping
period ends) that could be built by 2069. This was
for an Architectural contest. My team decided
that our entry had to house 60 people on rotating
1 year deployments, be built 90% of locally
available materials, feed itself with a mostly veg-
etarian diet and pay for itself. We tied for first
place in the category of technical feasibility and
elegance.

The base turned out to be 40% greenhouse, of
which there were 2 types. One was for plants that
thrive in the current high oxygen atmosphere of
present day Earth. The other was for plants that
evolved in a substantially higher carbon dioxide
atmosphere and thrive at CO2 levels too high for
human respiration. The two types of plants have
different kinds of photosynthesis.

Most of the plants that are a staple on Earth are of
the more ancient variety. Increasing the CO2
level has an effect similar to adding fertilizer.
They grow twice as fast or twice as big.

In this paper, I will explore the question of what
you would grow in lunar greenhouses and why.
Part of the paper will deal with nutrition, both
staple foods and items intended to avoid various
conditions associated with vitamin and protein
deficiencies. Medicines, including anesthetics,
stimulants, hallucinogens and herbs will be the
focus of a second part of the discussion. A third
part will deal with other materials needed or de-
sirable. These include fibers, those for fabric
and cloth (from canvas and towels to linen and
gauze); paper (cardboard and bags to toilet paper
and coffee filters); cordage (rope to thread);
wicker (furniture to baskets); fuel and alcohol;
glue and other adhesives; waxes; perfumes; nets;
cleansers (from soap to vinegar); padding and
stuffing; grease, oil, and lubricants; resins, paint,
turpentine, inks and dyes; sealants; gaskets; and
some especially important plants that can supply
several needs (like rubber, fruitwood, hemp,
bamboo, and peanuts).

Furthermore, in the stark and even bleak, lifeless
lunar environment, the idea of going to rest or
picnic in a garden, with fragrant oxygenated air,
lush greenery and colorful succulent fruits and
vegetables, make the greenhouses oases. These
spaces restore the spirit and assuage homesick-
ness for Earth.

In the situation where delivering a pound of mate-
rial from the Earth will cost $5000-10,000, the
acquisition of seeds and bacteria are among your
most promising investments. The mass to be
transported is minuscule compared to the yield
over a few generations. For example, a cantaloupe
or strawberry growing from a seed produces
hundreds of seeds in or on a single fruit. Each
of those seeds can become an equally prolific
source of more seeds, that can then rapidly fill the
available space. An apple seed multiplies in a
different but equally impressive way over a long-
er period.

ISRU must include the resources that become
available due to the foresight of those first adven-
turers. On Earth those who plant an olive tree do
not live long enough to see its fruit. But it is a
given part of the environment for those who ar-
rive at a later date.
Introduction: Technologies related to in situ resource utilization (ISRU) must be developed to make extraterrestrial colonies, research stations, and economic enterprises possible. At the Center for Space Resources in the Colorado School of Mines, key enabling technologies for lunar ice mining, regolith 3D printing, and in-situ geophysical investigation are being actively developed. In the past year, the Center for Space Resources has taken several TRL 1 ISRU technologies to TRL 4 and 5, and continue their development alongside corporate and government partners. This presentation will give an overview of the recent work done in the four previously mentioned key technology areas.

Lunar Ice Mining: The Center for Space Resources (CSR) has developed an ice extraction method called thermal mining. Methods for extraction of lunar permanently shadowed region (PSR) ice can be grouped into two classes: extraction based on bulk physical removal of icy regolith as solid material from the ground and extraction based on in situ sublimation of ice that allows regolith to remain in place. Recent findings have proven the existence of ice up to 30% by weight in the PSRs. Thermal mining is ideal for this scenario as ice is efficiently sublimated by applying heat directly to the surface of the PSR and the near subsurface (fig 2), then directing vapor to cold traps to freeze for transport to a processing system.

3D Printing: Additive manufacturing (AM) will be a key ISRU technology for producing parts astronauts will use to survive, from mechanical tools, to habitats to launch vehicles. A single AM system can produce complex, organic shapes as easily as simple parts, allow for system simplification, reduce failure modes, and eliminate storage and logistical concerns as parts are produced on an as-needed basis. CSR is pursuing development of this technology on multiple fronts: concentrated solar regolith AM in a simulated lunar environment, and large-scale, regolith-based structure printing. Though concentrated solar regolith AM and other directed energy methods have been tested, testing as seen in figure 3 has rarely been done within a simulated lunar environment of vacuum, high temperature, and high energy particles. CSR is defining the parameter space for regolith printing with the goal of immediate applicability to precursor AM testing missions on the lunar surface.

Geophysical Testing: Many surfaces found on the Moon, asteroids, Mars, moons, and other planetary bodies are covered in fine granular material known as regolith. Increased knowledge of the physical properties of extraterrestrial regolith surfaces will help advance scientific knowledge of these bodies as well as the development of exploration (e.g. instrument and robotic) and ISRU systems. CSR has developed a novel system, called the ISRU Experimental Probe (IEP, fig 1), supporting studies of dry and icy regolith from -196 to 150 °C and pressure from laboratory ambient pressure to 10-7 Torr. CSR has also built a room-sized regolith simulant filled test bed for larger scale geophysical property investigation and rover drive testing. Commercial partners such as Lunar Outpost (fig 4) have begun testing in the large regolith bed in preparation for lunar launches in the next five years.

Conclusion: The Center for Space Resources is developing technology to enable resource extraction, manufacturing, and fundamental science for the advancement of space exploration and ISRU capabilities. CSR is working to bridge the technical gap from the current global dream of practical, economically viable ISRU to its widespread use in the future.

References: SRR presentation/abstract for Thermal Mining (Dreyer, Sowers and Williams, 2018)
Commercial Lunar Propellant Architecture (Kornuta et al., 2018)
In the 20th century NASA researched many methods for the production of oxygen, and some for metals, from the ubiquitous metal oxides that make up the bulk of the Moon. However, the vast majority, as is recorded in summary form in the NASA publication SP-509, were based on chemical processing, requiring toxic and corrosive reagents requiring complex machinery and periodic replenishment from the Earth. Two processes, by NASA JPL’s Wolfgang Steurer, mentioned in NASA SP 509, were based on simple thermal methods, Vapor Phase and Plasma Phase Pyrolysis. These processes are related, and the work of Steurer focused on oxygen production via Vapor Phase Pyrolysis and oxygen and metals via plasma phase pyrolysis. The difference between the two processes is the temperature required for the disassociation of metals and oxygen for lunar metal oxides. In the past, the temperatures required were too high for available crucible materials (over 3,000 degrees c) and energy requirements were also excessive. The research presented here will survey and present experimental evidence from industry that ultra-high levels of vacuum such as exists on the Moon, dramatically reduces the temperature required for molecular disassociation of lunar metal oxides. These temperature reductions are sufficient to enable existing industrial crucibles of tungsten or Iridium to be used, and additionally lower electrical power requirements. Adding vacuum electromagnetic separation or zonal distillation enables the capture of oxygen and the capture and purification of metals to be used as inputs into industrial processes. It is estimated that this process could recover in excess of 95% of the oxygen and metals from the input metal oxides. Discussion of the design of an experimental apparatus and campaign will be presented that will validate materials selections, energy requirements, and determine yields using lunar analog materials of both highlands and mare varieties.

When the discussion of the Moon that goes beyond science to activities pertaining to In Situ Resource Utilization (ISRU), the vast majority of the discussion, since the confirmation by remote sensing and the LCROSS impactor, has centered around obtaining, processing, and using water. Water is an absolutely necessary component of an industrial economy utilization lunar resources. However, though necessary, water is not sufficient for an economic system that supports the opening of the solar system for the advance of humanity. Validation of the ability to separate metals and oxygen from metal oxides would be a major advance toward true lunar industrialization.
THERMOPHYSICAL MODELING OF COLD LUNAR REGOLITH: THE EFFECTS OF TEMPERATURE-DEPENDENT THERMAL PROPERTIES, COHESION, COMPOSITION AND ICE.
Stephen E. Wood, Planetary Science Institute, swood@psi.edu.

Thermal infrared remote sensing is a key source of information for the identification and characterization of locations favorable for ice and other volatiles on the Moon [1]. Measurements of surface temperatures are obtained directly, but much more information can be extracted through the use of models.

First, a model for the time evolution of surface and subsurface temperatures, \( T(z,t) \), (aka a “thermal model”, or \textit{thermal evolution model}) is used to find values of thermal properties giving the best fit to observed diurnal (and/or seasonal) surface temperature variations, \( T(0,t) \) [2-4]. A matching thermal model can then be used to predict temperatures at other times when observations aren’t available [1-4].

A second type of model – a \textit{thermal properties model} – can then be used to analyze and interpret the best-fit thermal properties in terms of the physical properties of the regolith material(s) such as particle size, composition, bulk porosity, etc. In most previous studies such analysis is limited to qualitative, empirical comparisons with the laboratory measurements of returned lunar samples. It is only in recent years that mechanistic, physics-based models for regolith thermal properties have become available [5-9]. Results and implications from the model “MaxTC”, developed by the author, will be presented here, as well as differences in predictions from other models.

As shown in Fig. 1, for cold (\( T<200K \)) sub-mm particles on airless bodies, the only significant mechanism of heat transfer is solid-phase conduction through inter-particle contacts. Radiative heat transfer, which dominates at warmer temperatures, accounts for \(<10\% \) of the total effective thermal conductivity (ETC) of the regolith. The magnitude of ETC in this case is proportional to the relative size of each contact surface between particles \( (R_{\text{con}}/R_{\text{part}}) \), the number of contacts, the porosity, and is \textit{directly proportional} to the conductivity of the solid particle material \( (k_{\text{sld}}) \). Therefore, ETC is expected to have the same temperature-dependence as \( k_{\text{sld}} \).

Fig. 1 also shows that ETC has a strong and complex dependence of ETC on particle size which can lead to ambiguity in some cases, as will be discussed.

LUNAR IN SITU RESOURCE UTILIZATION (ISRU) AND COMMERCIALIZATION
Paul M. Yun (pyun@elcamino.edu; paulyun@khu.ac.kr)

Introduction: In the 19th century, the impact of the Transcontinental Railroad on the United States was enormous by allowing a greater movement of population as well as goods. According to Research Nester, the global tourism is expected to reach over US $11.3 trillion by 2025.[1] An affordable transportation will allow a movement of people and goods between the Earth and the Moon, which results in lunar settlement through the construction for roads, structures for habitation, spacecraft and rocket warehouse and landing pads in spaceport. Lunar tourism can be a significant financial source for continued expansion of permanent human habitation on the Moon. Furthermore, the export of precious lunar metals to the Earth can also promote the commercialization in space.

Energy and Water: Energy harvesting should come in prior to the lunar ISRU. Some permanently shadowed regions of the lunar poles reserve up to 30 wt.% water ice[2], which can be used for drinking, breathing, and radiation-shielding as well as producing liquid hydrogen and oxygen propellant.

When a solar photovoltaic power plant is built further away from the lunar poles, it may not supply sufficient power to a lunar resource processing facility. A fission nuclear power system such as NASA’s Kilopower, can provide additional energy to the facility.

Regolith: Technology for sintering lunar regolith into bricks and ceramics needs to be developed. The chemical composition of lunar rock and soil samples collected through the Apollo Program shown in Fig. 2.[2] indicates that metals such as iron and aluminum extracted from silicates of regolith can be used to construct lunar infrastructures. Cost-efficient metal extraction and processing technology needs to be developed.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Formula</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Maria</td>
</tr>
<tr>
<td>silica</td>
<td>SiO₂</td>
<td>45.4%</td>
</tr>
<tr>
<td>alumina</td>
<td>Al₂O₃</td>
<td>14.9%</td>
</tr>
<tr>
<td>lime</td>
<td>CaO</td>
<td>11.8%</td>
</tr>
<tr>
<td>iron(II) oxide</td>
<td>FeO</td>
<td>14.1%</td>
</tr>
<tr>
<td>magnesia</td>
<td>MgO</td>
<td>9.2%</td>
</tr>
<tr>
<td>titanium dioxide</td>
<td>TiO₂</td>
<td>3.9%</td>
</tr>
<tr>
<td>sodium oxide</td>
<td>Na₂O</td>
<td>0.6%</td>
</tr>
</tbody>
</table>

99.9% 100.0%

Fig. 2. Lunar surface chemical composition (Credit: Taylor 1975)

Having constant sunlight and a good thermal environment, a solar photovoltaic power plant near a lunar pole operates almost continuously and can provide energy to a lunar resource processing facility. Different types of concentrating solar thermal power systems such as linear concentrating system, solar power tower, and solar dish system need to be tested out in the lunar environment to optimize energy harvesting. The total power usage needs to be calculated in advance so that the scale of the solar photovoltaic power plant can be determined. Furthermore, technology to store solar energy in water and to generate electrical power using electrolysis in the lunar environment needs to be developed.

Once cost-efficiently processed on the Moon, Helium-3 used for nuclear fusion and Rare Earth Metals (REMs)-scandium, yttrium, and the fifteen lanthanides-used for electronics, can be exported to the Earth.

Conclusion: A feasible and sustainable lunar ISRU through commercialization can happen when affordable transportation and power supply are available. Successful lunar ISRU will lead to ISRU on asteroids as well as Mars and beyond, which may result in human migration to other celestial bodies.

**Introduction:** Future missions to the Moon will require regolith samples from below the surface for either in situ analysis or sample return. These samples would be analyzed to answer specific science questions as well as provide information related to volatiles (and specifically water) resources for the purpose of In Situ Resource Utilization (ISRU).

To enable sample acquisition and delivery to instruments or sample return container, we combined high Technology Readiness Level (TRL) technologies: TRIDENT for sample acquisition and PlanetVac for sample delivery [1, 2, 3].

**TRIDENT and PlanetVac:** TRIDENT is a rotary-percussive drill designed to capture samples from approximately 1 m below the surface. Depending on the mission requirements and the lander size, TRIDENT could be modified to drill deeper or shallower. The 1 m version of TRIDENT weighs approximately 16 kg and can be mounted on the side of the lander or along one of the legs or in various locations on a rover. Smaller version of TRIDENT could weigh as little as 2 kg and penetrate 10 cm below the surface.

Drilling below the surface is the first step in sample acquisition. As important, however, is the sample delivery. Typical sample delivery options include mechanical approach – a scoop at the end of a robotic arm. This approach, however, has significant flaw – it requires that the arm can reach both the drill and the instrument. This significantly constrains where the two payload elements (drill and instruments) can be placed on the lander (or the rover). PlanetVac is a pneumatic sample delivery system that uses compressed air to fluidize and transport the sample directly into an instrument (Figures 1 and 2). The transport occurs inside a pneumatic tube which can be routed in any way to reach the instrument. As such, the drill and the instruments could be placed in different locations. This significantly simplifies the payload integration. The drill will be mounted where it’s best for the drilling, while the instrument can be placed in a location that’s most optimal for sample analysis (e.g. within thermally controlled box).

TRIDENT is at TRL6; the drill has been matured through a series of the lunar vacuum chamber tests (100 K and 10^-6 torr) in water doped and compacted lunar soil simulant NU-LHT-3M [4]. The tests were performed at VF13 facility at NASA GRC. The drill has also undergone vibration tests at NASA KSC.

PlanetVac is at TRL5/6; the system has been tested in a vacuum chamber and successfully delivered samples of JSC-1a lunar simulant into a cup [3]. PlanetVac has also been integrated on a footpad of a Masten Xodiac lander and tested under actual flight scenario in Mojave, CA. The lander took off, traversed, and landed on the bed of MSS simulant, PlanetVac was triggered to capture the sample, and the lander took off again and landed in its initial location. In each of the three tests, approximately 300 grams of sample was acquired [2].

**Figure 1. Details of the TRIDENT and PlanetVac system.**

**Figure 2. Details of the PlanetVac sample delivery to instruments.**

**Acknowledgments:** This work has been supported by NASA through various programs, including SBIR, ASTEP, ASTID, PIDDP, AES, ColdTECH as well as The Planetary Society.

Comparison of selected lunar regolith simulants and implications on their potentials for ISRU-related applications. X. Zhang¹ and G. R. Osinski¹, ¹Department of Earth Sciences & Centre for Planetary Science and Exploration, University of Western Ontario, London, Ontario, Canada. xzhan334@uwo.ca.

Introduction: Dozens of lunar regolith simulants have been developed worldwide to assist with testing the new generation lunar exploration equipment, both surface missions and remote sensing applications. Among these application tests, lunar in-situ resource utilization (ISRU) is a highly favourable approach to sustainably explore and settle on the Moon, significantly reduces the cost of launching supplies and supports the development of space mining technologies.

Although the most discussed application of ISRU is extracting resources from the lunar regolith, thus require high fidelity in chemistry and mineralogy of the simulants used in testing related equipment, a few other cases, such as infrastructure construction, may heavily rely on the physical properties [1]. Since it is extremely challenging to replicate both physical and chemical details of the lunar regolith, users need to critically consider how to choose the appropriate simulants for their intended tests.

For this study, we collected and characterized a set of simulants produced in China, Japan, Germany, and USA to compare their fundamental physical and chemical properties [2], some of which are especially important for ISRU tests.

Table 1. Summary of selected simulants

<table>
<thead>
<tr>
<th>Name</th>
<th>Country</th>
<th>Type</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAS-1</td>
<td>China</td>
<td>Low-Ti Mare</td>
<td>Apollo 14</td>
</tr>
<tr>
<td>EAC-1</td>
<td>Germany</td>
<td>Mare</td>
<td>Unknown</td>
</tr>
<tr>
<td>FJS-1</td>
<td>Japan</td>
<td>Low-Ti Mare</td>
<td>Apollo 14</td>
</tr>
<tr>
<td>OPRL2N</td>
<td>USA</td>
<td>Mare</td>
<td>Mare avg</td>
</tr>
<tr>
<td>OPRH2N</td>
<td></td>
<td>Highland</td>
<td>Apollo 17</td>
</tr>
</tbody>
</table>

Results: CAS-1 is the most glass-rich simulant in this set with highly angular particle shapes. Although its specific gravity is lower [3] compared to other products, it may support the study of particle interaction and anti-abrasive materials in lunar architecture and construction designs.

EAC-1 is intended to be produced in a very large quantity for EAC’s lunar simulation facility and is inevitably lower in chemical fidelity [4] and thus not recommended for resource extraction studies. However, it has the highest specific gravity in this set of simulants [2], close to the representative value of lunar regolith, it can be used to develop extraction and construction tools.

FJS-1 is Japan’s flagship simulant produced in the mid-1990s and has been widely used for both physical and chemical ISRU studies [5], but lacks glass component and is not of high mineralogical fidelity compared to its 2 other variations FJS-2 and -3 [6].

OPRL2N and H2N are the general-mechanical simulants produced at Off Planet Research by mixing basalt and anorthosite feedstocks into different proportions [7]. OPR is actively developing technologies to produce agglutinates as an add-on product. Since agglutinates are highly porous and rich in glass and nanophase iron (np-Fe), they will thus affect the geotechnical, mechanical and spectral properties of simulants [8,9]. Although the internal structure of the OPRH2N agglutinates sample is not examined yet, scanning electron microscope images show that the particles are indeed of complex shapes, and np-Fe-like features were found on some particle surfaces.

Discussion: All simulants chosen for this study were produced from crushing basalt and/or anorthosite rocks into desired grain sizes except OPRH2N agglutinates. This is the most economical and common method to produce simulants in large quantities but unfortunately cannot guarantee high fidelity in chemistry and mineralogy. Because of this limitation, the simulants selected for this study may not be the ideal candidates to test material processing and/or resource extraction but could contribute to civil and mechanical engineering for in-situ construction projects. Both developers and users need to understand if the chosen simulants(s) will effectively serve the intended test purposes.

Introduction: The NASA Lunar Development Lab (LDL) is a new concept to bring together academia, industry, non-profit organizations and NASA in an accelerator environment to generate new design solutions, technologies and architectures for lunar resource extraction, utilization and infrastructure development. By leveraging key partnerships in lunar science, mining, construction, chemical engineering and other key fields as well as making available rapid design, economic analysis, AI and machine learning tools, significant progress can be made in a short amount of time. Therefore, the goal of LDL is to accelerate development of lunar resource extraction, utilization and infrastructure systems to lead to a sustainable and economical human lunar outpost and the creation of a new thriving, cislunar economy.

A phased-development approach will be used with LDL over several years to accomplish its goal. The specific steps of the LDL approach include the following:

- Generate new design solutions, technologies and architectures for lunar resource extraction and utilization
- Develop design solutions and architectures for infrastructure systems including power generation and storage, communications, navigation, surface mobility and life support systems
- Build and test prototype hardware in a simulated environment to reduce technical and operational risk
- Partner with academia and industry to incentivize development of commercial product and services
- Partner with academia to train and equip the next generation of students with innovative ideas and solutions for lunar development as they enter the workforce
- Use AI and machine learning technologies and other advanced tools to quickly process data and optimize design solutions
- Use economic analysis tools to compare designs and architectures to work towards economic and sustainable solutions

As noted in several references, there are a wide variety of lunar resources in the lunar regolith that can be useful in the construction of a human lunar outpost. One major example is water-ice concentrations in the permanently shadowed regions of the lunar poles. Several remote-sensing, lunar missions in the last two decades including DOD’s and NASA’s Clementine mission launched in 1994; NASA’s Lunar Prospector mission launched in 1998; NASA’s Lunar Reconnaissance Orbiter (LRO) [2] launched in 2009 and NASA’s Lunar Crater Observation and Sensing Satellite (LCROSS) [3] mission launched in 2009 have all indicated the presence of water-ice deposits at the lunar poles. To take advantage of this potential water resource, various extraction techniques and architectures for water use and storage should be studied to determine economical approaches for sustained use of this water.

In addition, several studies have examined resource extraction and utilization processes necessary to extract and convert the lunar water into liquid oxygen and liquid hydrogen propellants. These studies have also provided cost estimates for putting the infrastructure in place for creating the propellant and then delivering it to a cislunar propellant depot for use in a future Mars architecture. Although these studies show a real potential strategy and positive business case for creating propellant on the lunar surface, in-depth design and architecture studies are needed for a more refined cost estimate of the exact methods, tools and machinery that will be needed and business plan for extracting the lunar ice and creating the propellant.

This presentation will describe the NASA LDL concept as well as it goals, objectives and approach for leveraging partnerships and creating an accelerator environment for lunar resource extraction, utilization and infrastructure development. It will also describe examples of lunar resource extraction and utilization, such as water use for life-support systems and propellant production, and the design work and hardware testing necessary to overcome the technical and economic challenges that will lead to successful implementation.

References: